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LARGE SCALE V/STOL WIND TUNNEL POWER SECTION DESIGN STUDY

FOR

NASA

MOFFET FIELD, CALIFORNIA

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1. CONTRACT STATEMENT OF WORK

A. The contractor shall investigate the drive system for a once-through "Y' configuration of a common drive section and two test sections (75 ft. by 150 ft. and 133 ft. by 200 ft.), one in each leg of the Y. The drive section shall have the following parameters:

	Approximate Tip Speed (ft./sec.)	Nominal Fan Diameter (ft.)	Number of Fans
(1)	302	50	18
(2)	410	50	18
(3)	635	50	18

Because of the importance of minimizing the noise level, emphasis shall be placed on the lowest fan tip speed (302 ft./sec.).

B. The wind tunnel performance requirements are: (1) a maximum velocity of 300 knots in the 75 ft. by 150 ft. test chamber at maximum drive horsepower, and (2) the maximum velocity attainable in the 133 ft. by 200 ft. test chamber with the same horsepower.

C. Three drive systems shall be considered:

(1) A combination of AC synchronous and DC drive motors mechanically coupled to continuously adjustable pitch fans. The drive system shall be rated for two hours continuous operation at the maximum horsepower required in B(1) and (2) and for corresponding longer

periods at lower power requirements. The DC drive motors shall serve two purposes; first, to operate the tunnel at adjustable speed without the synchronous motors energized, and secondly, to bring the synchronous motors up to synchronous speed and to share the shaft load after the AC motors are energized. The DC motor in each nacelle shall be rated at 10 percent of the required shaft horsepower at rated speed. This study shall include the power and control equipment required for this drive system.

(2) A wound rotor induction motor or synchronous motor drive using state-of-the-art solid state speed and frequency control, and mechanically coupled to two-position adjustable pitch fans. The possibility of using fixed pitch fans in this case shall also be investigated and the consequent trade-offs involving power requirements, functional efficiency, initial and operating costs, reliability, etc. shall be covered. This study shall include all power factor and other controls required for this system.

(3) A gas turbine drive mechanically coupled to a two-position adjustable pitch fan. This study shall contain a comparison of prime mover noise level versus drive fan speed for drive systems C(1), (2), and (3).

D. The contractor shall thoroughly investigate the continuously adjustable pitch fan blade mechanism, required for drive system C(1) above, to determine its feasibility and cost for the duty required for wind tunnel operation. This includes an analysis of practicability, reliability, time between overhaul of fan hub, etc. The contractor shall also determine whether the required speed of $\pm$ knot will be obtainable for the variable pitch fan mechanism. This study shall not include a more detailed investigation of the two-position fan than that required to establish the characteristics of drives C(2) and (3).

E. The contractor shall estimate the sound power level of the fans in part A as a function of fan tip speed.

F. The contractor shall re-estimate nacelle diffuser efficiency using the method described in "A Review of Incompressable Diffuser Flow," Aircraft Engineering, 1963. This should be done for both test sections of the "Y" configuration wind tunnel.

G. The results of the work required by this modification shall be described in a supplementary report and shall be submitted within 120 days of authorization of this modification.

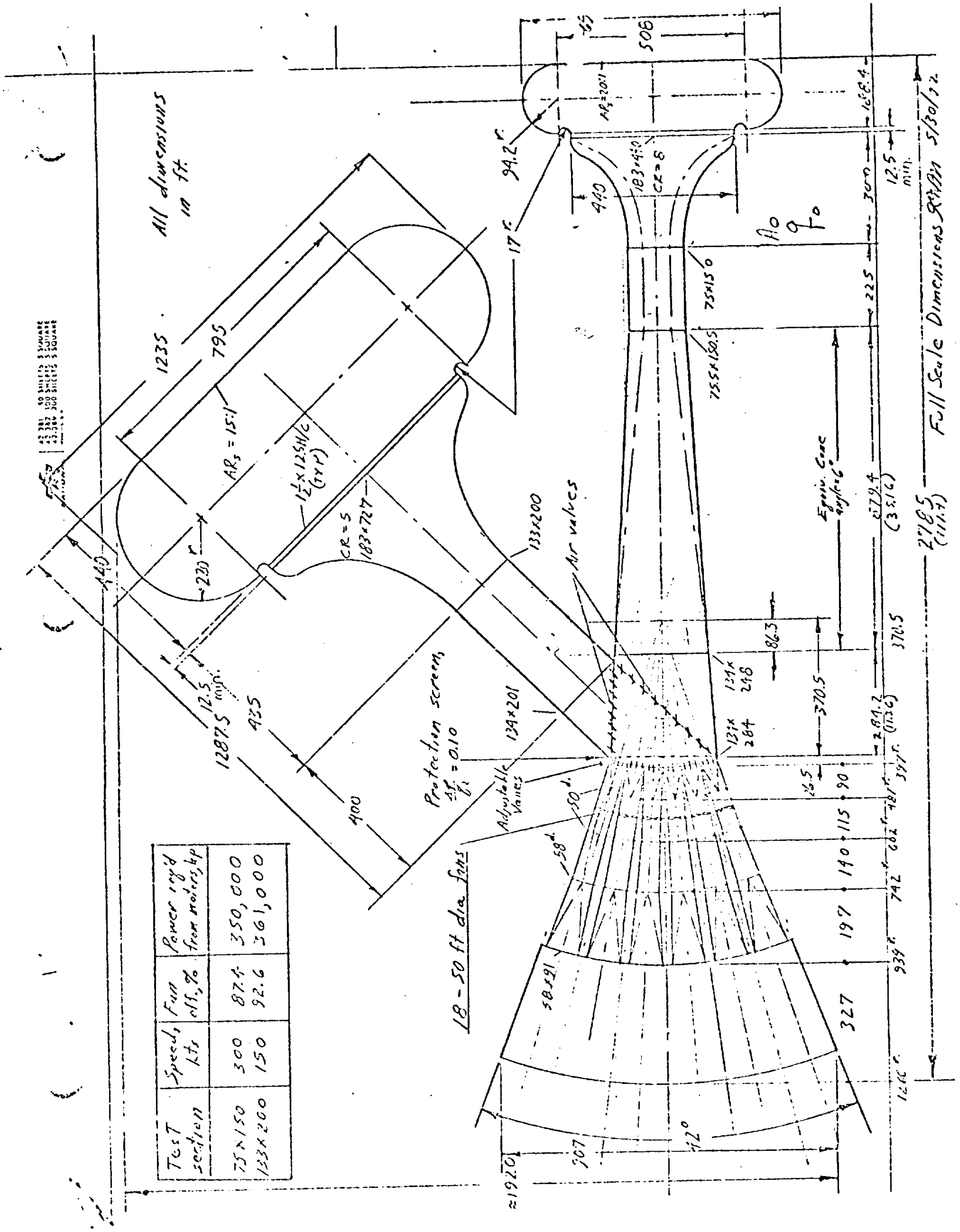
2. FAN REQUIREMENTS

2.1 High Speed Leg

The "Y" tunnel configuration under consideration is shown in Figure 2.1 and the proposed nacelle design in Figure 2.2. Both test sections are of the open rather than return type and utilize a common power section of 18 fans which draw air through the test section. A series of moveable vanes at the junction of the fans and tunnel diffusers act as valves to shut off one tunnel section from the fan intake and open the other.

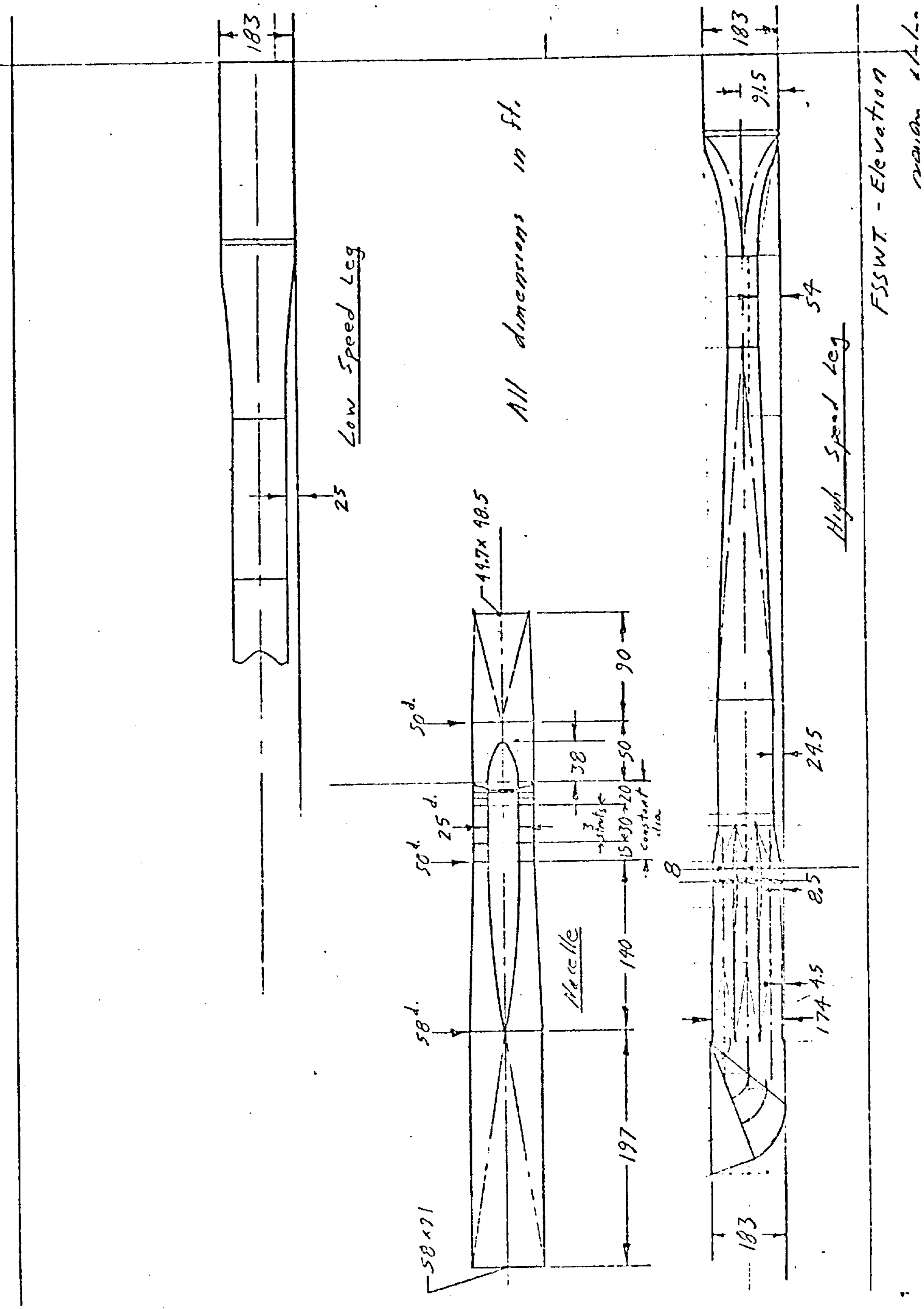
2.1.1 Fan Flow Distribution

In the proposed design there is essentially zero duct length between the exit plane of the diffuser and the entrance to the fan sections. This is of most significance for the high speed test section leg and requires some consideration to determine the variations in flow among the 18 fans and the average total pressure loss of the wind tunnel diffuser. From the correlation of Sovran and Klomp, Reference 1, we would estimate a blockage of the velocity profile of the 75' x 150' test section diffuser at the protection screen plane of 0.32, which means that the velocity of the centerline streamline is $\frac{1}{(1 - .32)}$ times the area mean average. We further assume that the sheared flow reaches to but does not include the centerline (a condition suggested by Reference 1) and that the boundary layer is close to separation ($H \simeq 2.0$). Under these assumptions, the



NASA "Y" V/STOL TUNNEL

FIGURE 2.1



NACELLE DESIGN

FIGURE 2.2

velocity profile in the 284 ft. dimension would approximate that measured by Nikurdse (Reference 2) and given in Schlicting's Boundary Layer Theory (Reference 3). This profile is approximated in Figure 2.3. In addition, a profile is shown on the same graph which is our best estimate of the modifying effect of the distributed fans.

This modification is based on modeling the fan pressure flow characteristics in terms of an equivalent screen and applying the screen profile modifying relations.

Over a small range of flows screen pressure drop characteristics can be expressed as

$$\Delta P = Kq \tag{2.1}$$

where

ΔP = total pressure drop across screen

q = dynamic head of the approach flow

K = screen pressure coefficient

The variation in pressure drop with dynamic head is simply

$$\frac{d(\Delta P)}{dq} = K \tag{2.2}$$

A typical fan characteristic as for example Figure 2.4 reproduced from Reference 4 has an approximate

$$\frac{d(\Delta P)}{dq} = 1.3$$

linearized about the design point.

DIFFUSER DISCHARGE VELOCITY PROFILE

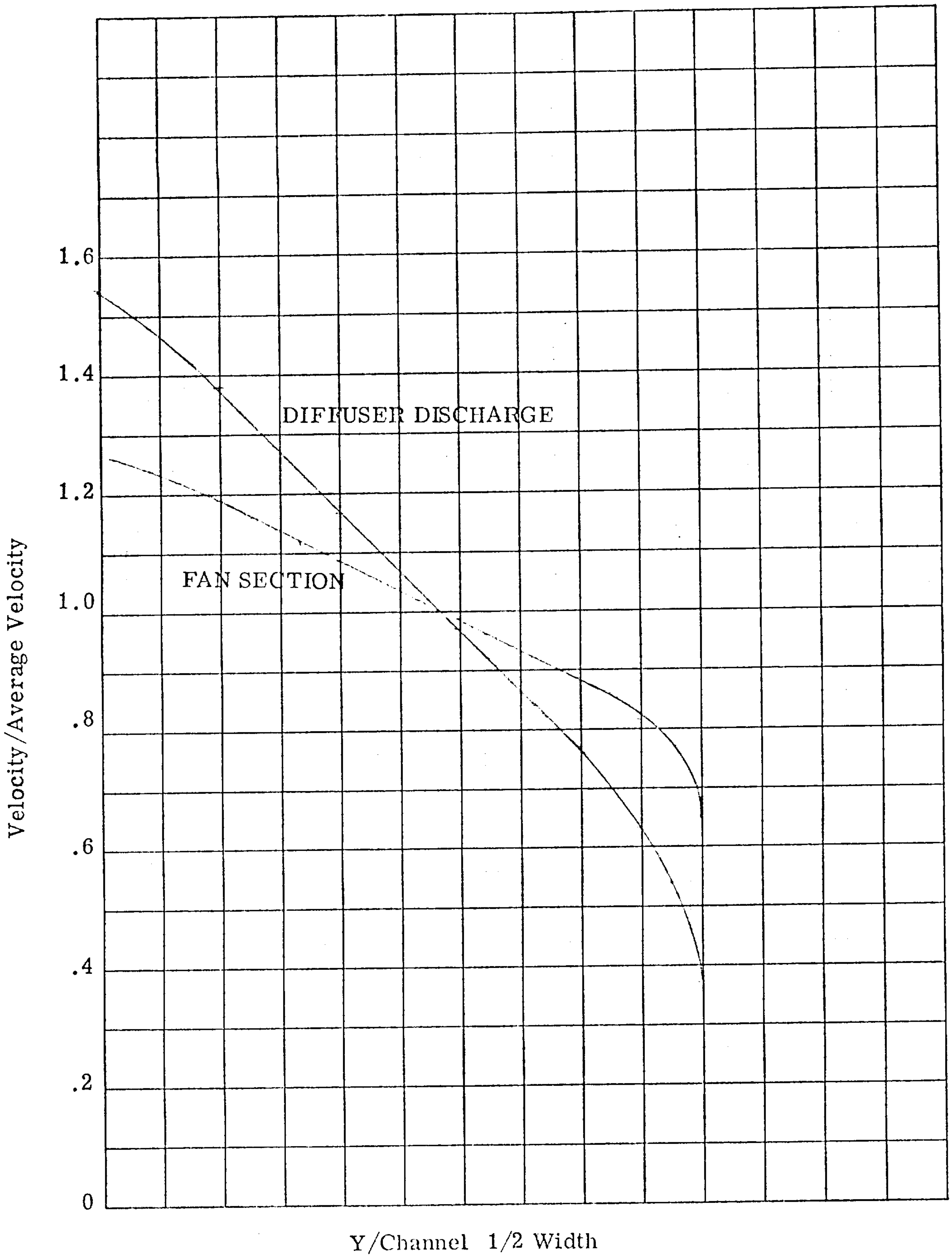


FIGURE 2.3

FIXED PITCH VARIABLE RPM MOTOR DRIVE

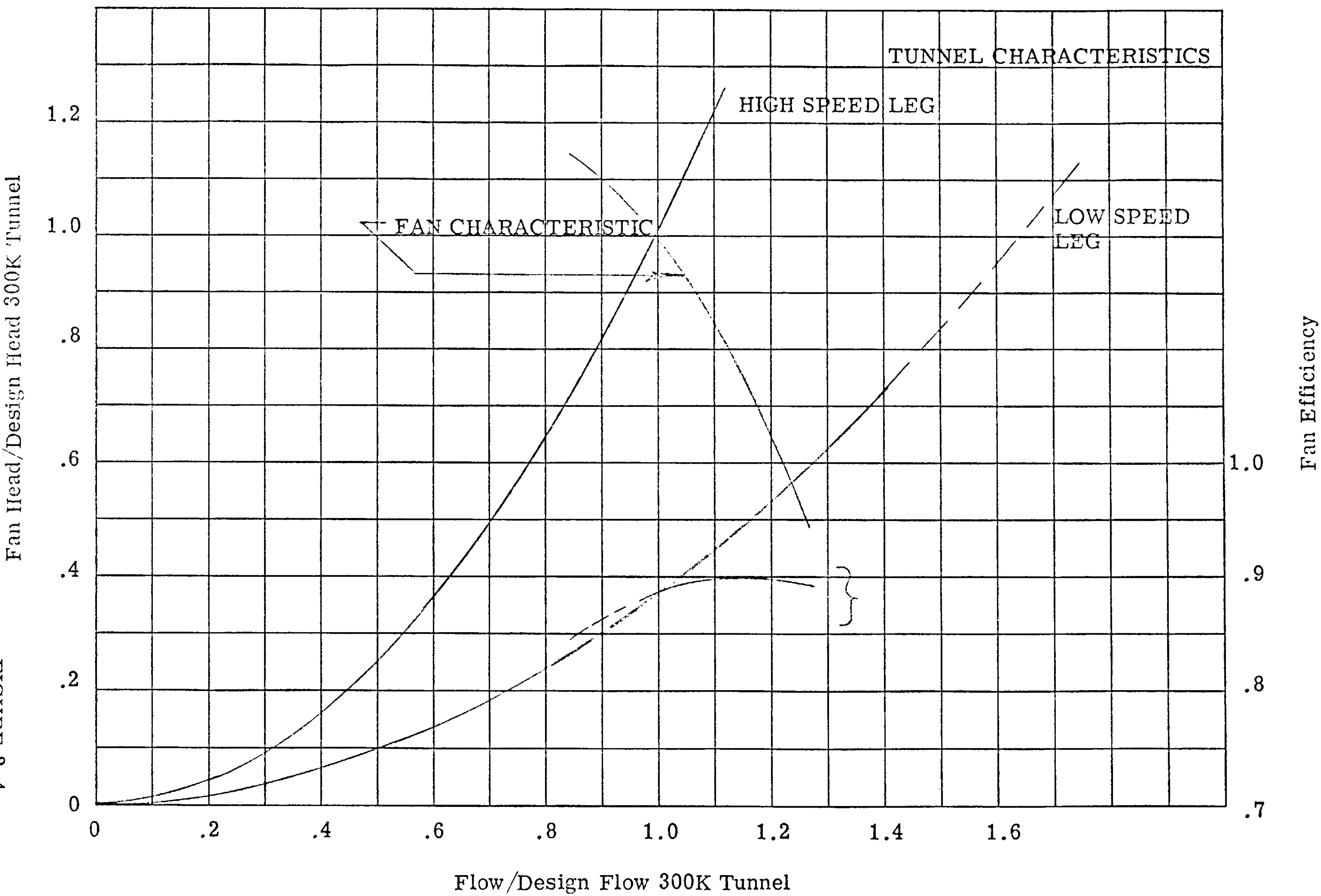


FIGURE 2.4

FIXED PITCH GAS TURBINE DRIVE

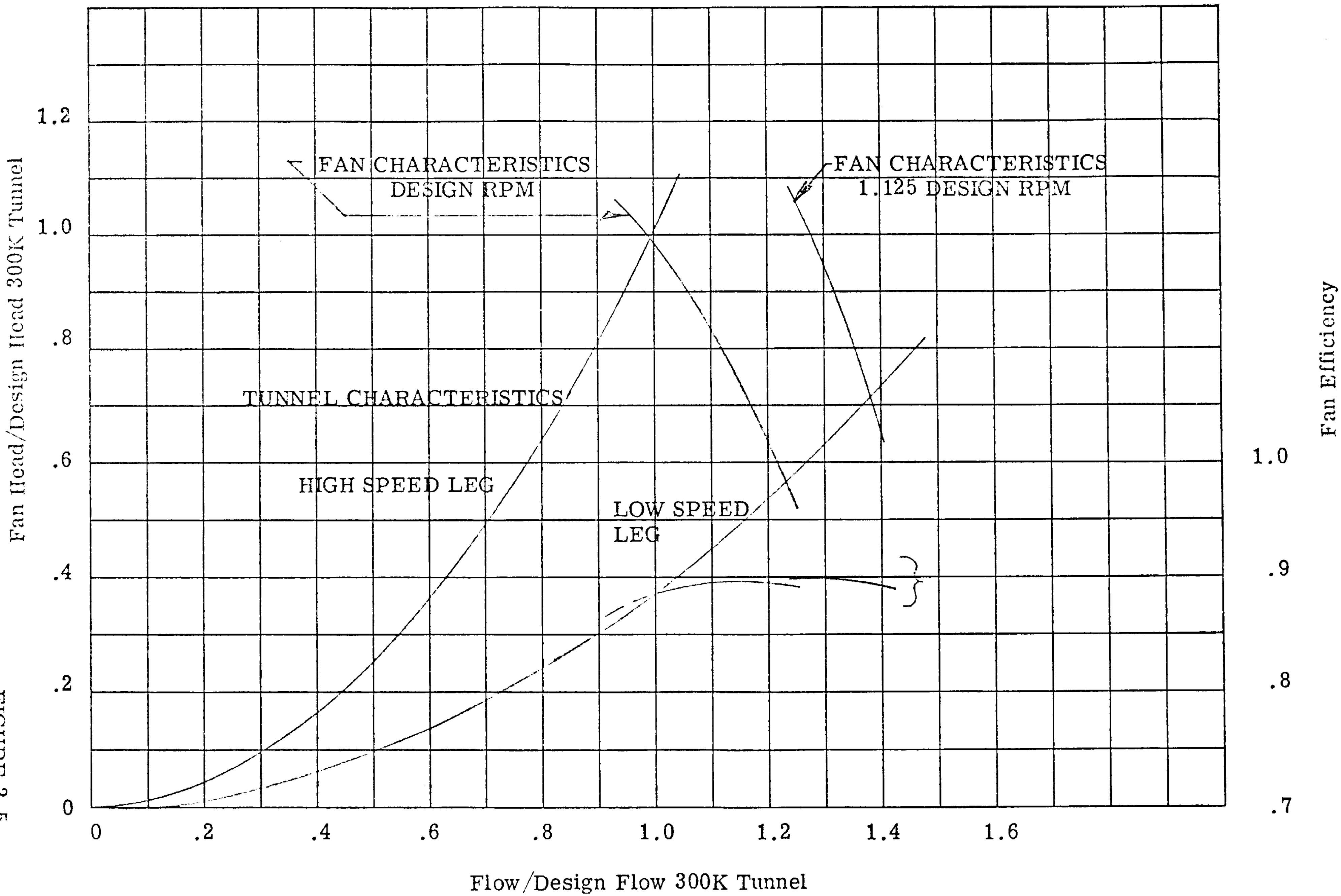


FIGURE 2.5

We now assume the fans operate like a screen and apply Prandtl's velocity modification relation

$$\left(\frac{U_3}{\overline{U}} - 1\right) = \frac{1 + \alpha - \alpha K}{1 + \alpha + K} \left(\frac{U_1}{\overline{U}} - 1\right) \qquad (2.3)$$

where

$$\alpha = \frac{1.1}{(1 + K)^{1/2}}$$

U_1 = velocity approaching the screen

U_3 = velocity some distance downstream of screen where the screen identy has been diffused

$\overline{U}$ = area mean velocity

Thus for a K = 1.3, the spacial reduction factor is about 0.25 or

$$\left(\frac{U_3}{\overline{U}} - 1\right) = 0.25 \left(\frac{U_1}{\overline{U}} - 1\right) \qquad (2.4)$$

Since a screen effects about half of its velocity modification upstream and half downstream, we assume the distributed fans will do the same. The actual ingestion into the fans will then be distributed relative to the diffuser discharge as

$$\left(\frac{U_3}{\overline{U}} - 1\right) = 0.50 \left(\frac{U_1}{\overline{U}} - 1\right) \qquad (2.5)$$

which is the profile illustrated on Figure 2.3. On the basis of this profile, the center fans would have to handle 120% of the area mean flow and the end fans 85%. With such a large variation in flow stalling could well occur in the fans along the wind tunnel boundaries unless some adjustment is made in fan pitch.

It is evident that the fans along the duct centerline will see a lower than average tunnel resistance as diffusion of this flow approaching the fans reduces the energy required for propulsion. Similarly, the acceleration of the air along the tunnel boundaries increases the effective system resistance which the boundary fans must work against.

To fully utilize the kinetic energy represented by the nonuniform discharge profile of the diffuser would require several fan designs among the 18 fan array which is beyond the scope of this study. Rather we based our motor sizing on an average fan as calculated by the diffuser discharge total pressure equal to the area mean average velocity pressure and static pressure recovery.

2.1.2 Wind Tunnel Diffuser

The "average fan" tunnel requirements does not take advantage of the excess kinetic energy flux represented by the peaked diffuser discharge profile nor the static pressure rise in profile modification as the fan plane is approached or the added losses at the fan inlets due to cross flow. The positive and negative aspects of these effects are assumed to approximately balance.

For an evaluation of the 75 ft. x 150 ft. test section diffuser, we have applied the correlation of Sovran and Klomp, Reference 1. The entire diffuser from the test section discharge to the protection screen plane can most conveniently be considered as one diffuser. To apply this correlation we must assume an inlet velocity blockage to the diffuser.

A value equal to a long radius ASME nozzle 0.004 was taken. With this value we calculate the Sovran parameter

$$AR\ (100\ B_1)^{1/4} = 3.512\ \times (100 \times .004)^{1/4}$$
$$= 3.091$$

where

AR = Diffuser area ratio = 3.512

B_1 = Inlet blockage = 0.004

E_1 = Inlet effectiveness = $1 - B_1$ = .994

E_2 = Discharge effectiveness

$$E_2 = f\ [AR\ (100\ B_1)^{1/2}] = 0.68$$

Σ_0 = Diffuser efficiency based on area mean discharge velocity and static pressure rise

Reference 1 gives a correlation of discharge effectiveness E_2 as a function of this parameter. Knowing $E_2 = 0.68$, the diffuser efficiency may be calculated from

$$\Sigma_0 = \frac{1}{E_1^2} \left[\frac{1 - \left(\dfrac{E_1}{E_2 \times AR}\right)^2}{1 - \left(\dfrac{1}{AR}\right)^2} \right] \qquad (2.6)$$

which yields

$$\Sigma_0 = 0.911$$

We now can convert this efficiency into a total pressure loss coefficient namely:

$$K = \left[\frac{AR^2 - 1}{AR^2} \right] \left[1 - \Sigma_0 \right] \qquad (2.7)$$

which in our case becomes

$$K = 0.0818$$

This value compares to a NASA estimate of $K = 0.0505$ and we ask if the difference is primarily in our discarding the excess velocity kinetic energy which may be in the NASA calculation.

An estimate of the excess energy in the diffuser discharge profile can be made by starting with the above result that $E_2 = 0.68$. We then have the value of the velocity on the diffuser centerline as $\frac{1}{.68}$ times the area mean average. For the profile assumed in Figure 2.3, we have that

$$\delta_2^{**} / \delta_2^{*} \approx 0.68$$

while at the entrance to the diffuser

$$\delta_1^{**} / \delta_1^{*} \approx 1.54$$

These values can be combined with equation (8) of Reference 1 to yield the total energy loss coefficient of the diffuser as given below.

$$K = \alpha_1 \left[1 - \frac{\alpha_2 / \alpha_1}{AR^2} \right] - \Sigma_0 \left(1 - \frac{1}{AR^2} \right) \qquad (2.8)$$

where α is the energy flux velocity profile parameter given by

$$\alpha = \frac{1}{A} \int^{A} \left(\frac{U}{\overline{U}} \right)^{3} dA$$

$$\alpha = \frac{1}{E^2} \left[1 - \frac{\delta^{**}}{\delta^{*}} \frac{(1 - E)}{E} \right] \quad (2.9)$$

δ^{**} = profile energy thickness

δ^{*} = profile displacement thickness

AR = diffuser area ratio = 3.512

E = section flow effectiveness

Using the values $E_1 = 0.994$ and $E_2 = 0.680$ previously calculated we obtain

$$K = 0.055$$

which is within 10% of the NASA value of 0.505. Thus the additional loss we introduce in using K = .0818 is primarily due to an unidentified ability to fully utilize the energy in the distorted diffuser discharge profile in an array of close coupled fans. This situation is much different than a closed wind tunnel where all of the excess profile energy is contained within the tunnel and reduces the acceleration pressure drop in the test section nozzle or adds to the profile mixing pressure rise.

2.1.3 <u>Fan Naccelle Diffuser</u>

The fan power section shown in Figure 2.2 is followed by a discharge chute which both diffuses and turns the exhaust flow.

The additional expansion following the power section diffuser and dump will reduce the rate of mixing of the power section profile and significantly reduce the profile static pressure rise which accompanies such mixing. For this reason the power section diffuser losses were evaluated as if no profile mixing pressure rise occurs. For this condition the diffuser correlation of Cockrell and Markland, Reference 5, agree with the efficiency value of 83% used in previous studies 4 and 6. As with the test section diffusers, it is most convenient to treat several diffusers in series as a single unit as the aft section is operating with a very distorted inlet profile which makes its separate evaluation speculative. The combined area ratio of the power section conical expansion and rectangular transition is 3.588. Applying this value and 83% efficiency in Equation 2.7, we obtain a total pressure loss coefficient of

$$K = 0.1568$$

This completes our diffuser analysis. The losses obtained for the test section and power section diffusers are combined with estimates supplied by NASA Ames for other wind tunnel components and included in the tunnel loss tabulation of Table 2.1.

TABLE 1

V/STOL WIND TUNNEL PERFORMANCE

High Speed Straight Leg

Number	Section	Area	A_1/A_0	K	K_0	Estimated Source
16	Contr FD	80,343	8.00	.00478	.00478	NASA
17	HNY-Comb	78,736	8.00	.09324	.00137	NASA
18	Inlet Pst	133,905	13.33	.00770	.00004	NASA
18	Inlet Sys	200,857	20.00	8.23290	.01858	NASA
1	Test Dif	10,043	1.00	.01021	.01021	NASA
1	Model	10,043	1.00	.01000	.01000	NASA
2-3-5	Diffuser	10,143	1.01	.08180	.08018	GE
5	Valves	35,598	3.54	.01343	.00097	NASA
6	Screen	38,091	3.79	.13379	.00844	NASA
7	Flow Str	33,394	3.79	.00836	.00069	NASA
8	MPL Cntr	38,091	3.79	.00384	.00096	NASA
9	Fan Cont	29,166	2.90	.00954	.00125	NASA
10	Fan Const A	26,507	2.64	.01835	.00241	NASA
10	Fan Struts	26,507	2.64	.01405	.00184	NASA
11-12	Fan Diffuser	26,507	2.64	.15680	.02251	GE
13	Sudden Ex	95,108	9.47	.06128	.00062	NASA
14	Vert Ex	126,398	12.59	.17112	.00046	NASA
14	Exit	266,035	26.49	.90271	.00116	NASA

2.1.4 Fan Head - Flow Requirements

The fan flow was based on the following conditions:

Test Velocity	506.33 ft/sec
Total Pressure at Test Section	2117 lbs/ft^2
Total Temperature	529.7 ^oR
Test Section Area	10,043 ft^2

from which we calculate:

Mach No.	0.457
Tunnel Weight Flow	346,697 lbs/sec
Weight Flow/ Fan	19,261 lbs/sec
Dynamic Pressure at Test Section	269.68 lbs/ft^2

Based on the sum of the K_0 values in Table 2.1, the total pressure rise across the fan is:

$$\Delta P_T = \Sigma K_0 \times q$$

$$= .16647 \times 269.68$$

$$= 44.89 \ lbs/ft^2$$

and the density at the fan inlet is approximately

$$\rho_{fan} = 0.0726$$

This results in a required head rise of

$$\Delta H_{fan} = \frac{44.89}{0.0726}$$

$$\Delta H_{fan} = 618 \text{ ft.}$$

and input power of:

$$\text{Power} = \Delta H_{fan} \times \text{Weight Flow}$$

$$\text{HP} = \frac{618 \times 19{,}261}{550}$$

$$\text{HP} = 21{,}620$$

At an assumed fan efficiency of 90%, 24,000 HP motors would be required.

2.2 Low Speed Leg

The low speed leg calculation follows directly from NASA input data with the substitution of the previous nacelle diffuser losses for elements 11 and 12. The losses are as tabulated in Table 2.2.

The sum of the K_0 values is

$$\Sigma K_0 = 0.46168$$

which in combination with a tunnel nominal dynamic head of 72.83 lbs/ft^2 at 150K yields:

$$\Delta P_T = 0.46168 \times 72.83$$

$$\Delta P_T = 33.624 \text{ lbs/ft}^2$$

The weight flow at 150 knot velocity is

$$W = 492,100 \text{ lbs/sec}$$

$$W/\text{fan} = 27,350 \text{ lbs/sec}$$

The density at the rotor plane is approximately

$$\rho = 0.07221$$

which results in a fan head requirement of

$$H_{fan} = \frac{33.624}{0.07221}$$

$$H_{fan} = 465.63 \text{ ft}$$

and fan input power at 90% fan efficiency of

$$HP = \frac{465.63 \times 27,350}{550 \times .90} = \frac{12,734,981}{495}$$

$$HP = 25,727$$

TABLE 2.2

V/STOL WIND TUNNEL PERFORMANCE

Low Speed Leg

Number	Section	Area	A_1/A_0	K	K_0	Estimated Source
16	Contr FD	133,000	5.00	.00464	.00464	
17	HNY-Comb	130,340	5.00	.09561	.00389	
18	Inlet Pst	266,000	10.00	.00419	.00004	
19	Inlet Sys	399,000	15.00	8.23290	.03568	
1	Test Dif	26,600	1.00	.01140	.01140	
2	Model	26,600	1.00	.00376	.00376	
3	Const A	26,946	1.01	.00273	.00273	
5	Valves	26,946	1.01	.01337	.01302	
5	Const A	26,946	1.01	.00273	.00266	
6	Diff HC	26,946	1.01	.13919	.09473	
6	Screen	38,074	1.43	.13379	.06444	
8	MPL Cntr	38,074	1.43	.00843	.00699	
9	Fan Cont	29,153	1.10	.00909	.00915	
10	Fan C A	26,507	1.00	.01747	.01760	
10	Fan Struts	26,507	1.00	.01538	.01549	
11-12	Fan Diff	26,507	1.00	.15680	.15790	
13	Sudden Ex	95,108	3.58	.06128	.00468	
14	Vert Ex	126,398	4.75	.16768	.00344	
14	Exit	266,000	10.00	.97532	.00951	

If our requirement is to equalize input power in both tunnel legs then the flow specification in the open leg must be reduced by the ratio $\left[\frac{24,000}{25,727}\right]^{.333}$ or 0.9772. Thus the specifications for the fan become:

Test Section Velocity	=	146.5K
Fan Head Rise	=	442.2 ft
Fan Weight Flow	=	26,740 lbs/sec
Fan HP	=	24,000

2.3 Fan Operating Conditions

This study was principally concerned with variable pitch fans driven by synchronous motors. However, brief consideration was also given to two position fixed pitch and one position fixed pitch variable speed operation.

In accordance with the work statement drives were sized for an 18 fan array of 50 ft. diameter each. Drives for fans of three different tip speeds were sized, 350, 410, and 628 feet per second. The lowest was chosen by consideration of the maximum loading parameters at 300K operation which would be prudent. At this flow there is a tunnel head requirement of 618 feet which at 90% efficiency results in a fan input head of 687 feet. For a 350 ft/second tip speed design with .50 hub to tip radius ratio the hub conditions:

Tip Speed	350 ft/sec
Radius Ratio	0.5

Hub Rotor Turning	29^{o}
Hub Stator Turning	35^{o}
Hub Solidity	1.25
Hub Diffusion Factor	.454

are about as severe as would be consistent with broad flow range and high efficiency requirements of this design. The three drive specifications are:

Fan Drive Specifications

Fan	No.	Tip Dia. ft.	Hub Dia. ft.	RPM	Tip Speed ft/sec	HP/Fan
A	18	50	25	133.33	349.06	24,000
B	18	50	25	156.52	409.77	24,000
C	18	50	25	240.00	628.32	24,000

2.3.1 Fixed and Variable Pitch Performance

If a single pitch fan were designed for the dual tunnel operation, the blade profiles would be selected to optimize efficiency at a flow intermediate between the two conditions. The approximate situation is as shown on Figure 2.4 where the efficiency is seen to maximize at 1.15 of the high speed tunnel flow. The intersection with the low speed tunnel characteristic is at 1.24 times the high speed tunnel flow or about 130 knots in the test section. This compares with the 146.5 knots attainable with variable pitch fans.

When full power can be obtained at variable speed, as would be possible with a gas turbine drive and some electric motor drives, then low speed test section velocities of about 146 knots are attainable with fixed pitch fans. This is illustrated in Figure 2.5.

With a continuously variable pitch fan and constant rpm drive the intersection of the fan curves and load lines would also approximate that shown on Figure 2.5.

2.3.2 Starting Conditions

For either a single pitch fan, two position pitch fan, or two design speed fan, the drives provide for continuously variable rpm. Thus the tunnel test section velocity is adjustable directly by varying rpm. All 18 fan drives would normally be controlled to the same rpm and speed changed by changing all 18 fans in unison. When two fan pitches are provided, the intent is to match the load lines of the two tunnel legs and blade pitch of all fans would be set at shut down according to which leg was in use.

Only for the continuously variable pitch fan is the operating procedure any different than in the present 40 x 80 ft. Ames tunnel. In this case, variable speed power is limited to 15 percent of the shaft horsepower required at rated speed. This variable speed power is sufficient for variable speed drive at design blade setting up to 50% design speed. When higher test velocities are required two modes of blade-speed adjustment are feasible. The blades of all fans could be depitched and fans brought up to synchronous speed with essentially zero tunnel flow. Once the motors have been synchronized, then the pitch of all fans are adjusted in unison to control test section velocity over the entire tunnel range.

Alternately, the tunnel is operated in the fixed pitch variable speed mode up to between 40 and 50% design speed. At this flow individual fans are depitched and brought up to synchronous speed without altering test section velocity. After all motors are synchronized fan pitch is controlled to alter test section velcoity.

For the majority of operations, the latter mode would appear preferable as it greatly reduces noise of low test speed flows and minimizes the off design operation of the fans.

3 FAN DRIVE SYSTEMS

3.1 Power and Speed Requirements

Paragraph 2.3 of this report summarizes the fan drive specifications. Paragraph 2.3.1 and Figure 2.5 indicate that where the drive is capable of operating over a constant horsepower adjustable speed range of 1.125, then low speed test section velocities of about 146 knots are attainable with fixed pitch fans.

The fan drive specifications are tabulated below, including the 1.125 constant horsepower speed adjustment range, where applicable.

Fan Drive Specifications

Fan	No.	Tip Dia. ft.	Hub Dia. ft.	RPM/1.125 RPM	Tip Speed ft/sec	HP/Fan
A	18	50	25	133.33/150.00	349.06/392.69	24,000
B	18	50	25	156.52/176.09	409.77/460.99	24,000
C	18	50	25	240.00/270.00	628.32/706.86	24,000

3.2 Drive Descriptions

3.2.1 Drive Alternate #1, Tandem a-c Synchronous and d-c Drive Motors Coupled to Continuously Adjustable Pitch Fans

This wind tunnel air flow adjustment scheme combines adjustable speed drives with adjustable pitch fans. Tunnel air velocities from 5% to 50% of rated will be attained by adjusting the speed of the fan motors from 5% to 50% of rated speed with fan pitch held constant at full pitch. Tunnel air speeds from 50% to 100% of rated will be attained by operating the fans at constant top rated speed and by adjusting the pitch of the fan blades.

It is advantageous to operate at adjustable speed, fixed full pitch wherever practical because such operation minimizes fan noise, maximizes drive and fan efficiency, provides excellent air velocity control resolution and provides the most uniform air flow profile across the tunnel cross section.

The fan study indicated that approximately 12% of rated power is required to drive the fans at full speed when the blades are depitched. Allowing for the additional power required to drive the synchronous motor at full speed and with motor field excitation applied, a total power of 15% of rated power is required from the d-c motor at top rated speed.

Assuming this is accomplished using the two-hour, 25% overload capability of the d-c motor and assuming the load power varies as the cube of speed, then the d-c motor can drive the fan at 49% of rated speed at rated fixed pitch continuously or at 52.8% of rated speed at rated fixed pitch for two hours.

Accordingly the d-c motors have been sized at 15% of the drive horsepower rating and will have a base speed of 49% of top rated drive speed. This means that the d-c motors can deliver their rated horsepower at any speed between 49 and 100% of rated fan drive speed.

The synchronous motors will be sized at 85% of the drive power requirement.

The motors will be designed for forced ventilation via an external blower and duct system which will provide filtered air at a maximum temperature of 40°C to the motor air inlet openings. The warm air discharge from the motors will be discharged to the wind tunnel air stream.

Each motor and fan bearing will be provided with high pressure oil lift pumps to minimize starting torque. This will also facilitate manual rotation of the fans during inspection and maintenance.

Figure 3.2.1 describes a proposed power one-line diagram for this drive system. Three (3) identical systems are required for the eighteen (18) motors.

The d-c motors will be served by individual a-c to d-c thyristor rectifiers.

Power factor correction, using a 5 MVAR capacitor and a 10 MVAR synchronous condenser, is shown connected to the tertiary winding of the main power transformer. This method of power factor correction does not cause any severe voltage transients on the thyristor rectifier supply buses because the power factor correction equipment will be energized prior to

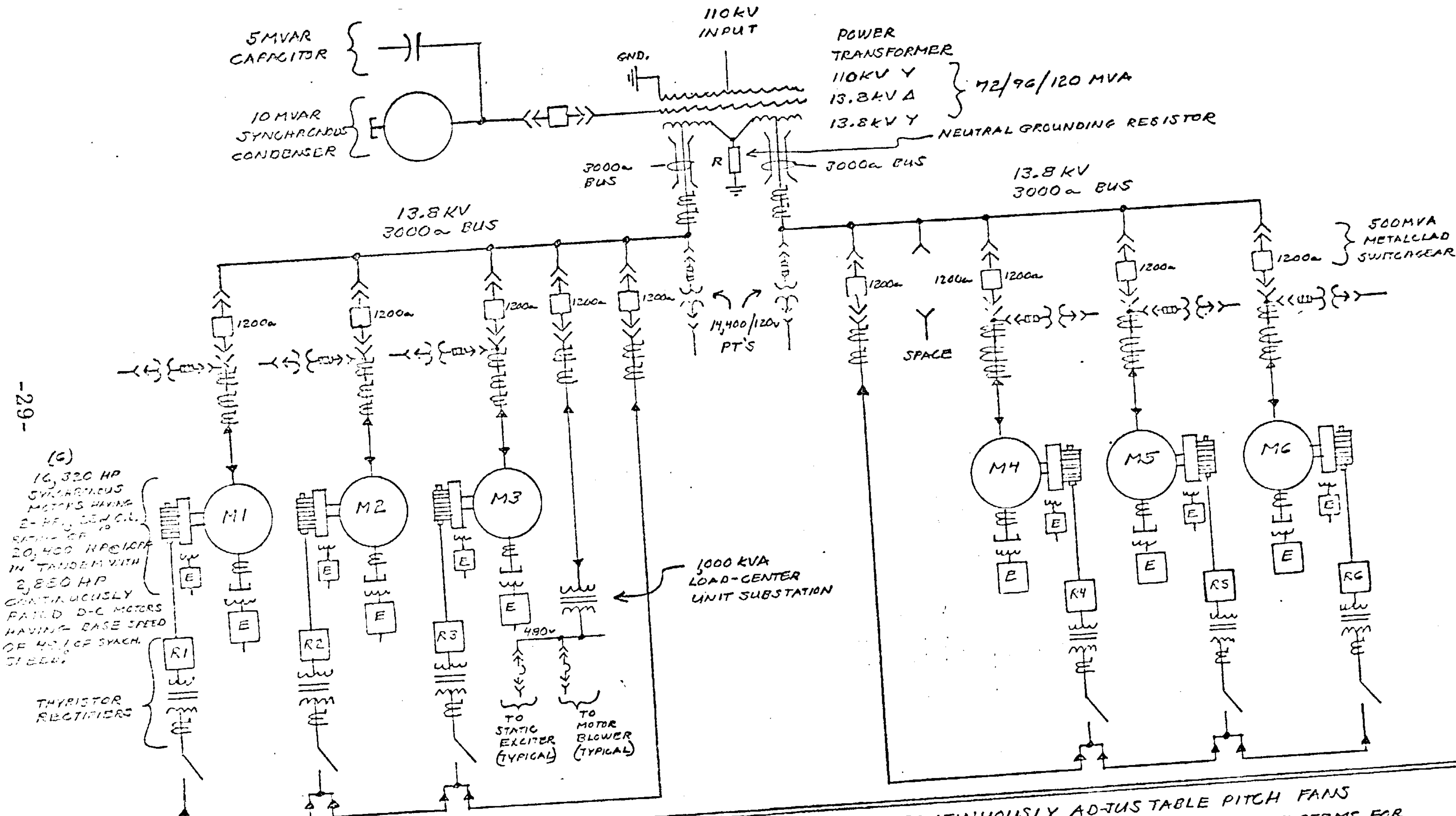


FIGURE #3.2.1

ALTERNATE #1, 18-CONTINUOUSLY ADJUSTABLE PITCH FANS
ONE-LINE DIAGRAM FOR DRIVES #1 - #6 (TWO OTHER IDENTICAL SYSTEMS FOR DRIVES #7 - #18). 85% SYNCHRONOUS MOTORS, 15% D-C MOTORS.
LARGE SCALE V/STOL WIND TUNNEL POWER SECTION DESIGN STUDY. FOR NASA AMES RESEARCH CENTER, MOFFETT FIELD CALIFORNIA

SKETCH MDH 62573-2

starting the main drives. The synchronous condenser will be smoothly and automatically regulated such that the combination of static capacitors and synchronous condenser can be adjusted from zero to fifteen (15) megavars leading. The capacitors will also serve as a filter to reduce the rectifier harmonic currents transmitted to the utility lines.

Table 3.2.1 below summarizes the a-c and d-c motor ratings:

TABLE 3.2.1

MOTOR RATINGS

Fan	A	B	C
Total HP @ Max Speed	24,000	24,000	24,000
A-C Synchronous Motor Data:			
Continuous H.P.	16,320	16,320	16,320
2-Hour H.P.	20,400	20,400	20,400
60 Hz Synch. Speed (RPM)	133 1/3	156.52	240
Voltage	13,200 V	13,200 V	13,200 V
Frequency	60 Hz	60 Hz	60 Hz
Phases	3	3	3
Power Factor	1.0	1.0	1.0
D-C Motor Data:			
Continuous H.P.	2,880 HP	2,880 HP	2,880 HP
2-Hour H.P.	3,600 HP	3,600 HP	3,600 HP
Base Speed/Top Speed (RPM)	65.3/133.3	76.7/156.5	118/240
Armature Voltage	900 V	900 V	900 V

3.2.1.1 Automatic Control and Regulating System

Fully automatic, unattended operation of the drive system is proposed. Motor speed adjustment will be accomplished by a single digital command which will regulate the same speed on all eighteen drive motors. Thumb-wheel switches will be provided for manual motor speed adjustment. Provision will also be made for digital speed adjustment from the purchaser's computer.

When operating in the constant speed, adjustable pitch fan control mode, the fan pitch control mechanisms will be automatically varied to cause the power inputs to the eighteen synchronous motors to be equal to each other at all times. Should operating experience indicate that equal motor powers does not produce a uniform air flow pattern in the tunnel, the proposed control will have provision to vary the proportionality between the motor stator powers as required to minimize the flow variations in the tunnel.

It is proposed that a single analog voltage reference signal be used for the pitch control system. This voltage will be cubed via analog circuitry and the resulting voltage will be used as the reference signal for the individual stator power regulators on each motor. Because the fan power varies as the cube of tunnel air velocity, the resulting tunnel air velocity will be approximately proportional to the analog voltage reference. This reference voltage can come from either a manually adjusted potentiometer, a digital regulator or from a pressure regulating loop which will regulate constant tunnel air velocity.

The tunnel drive system will be started, stopped, and tunnel air speed will be adjusted from the tunnel control room located remotely from the drive equipment.

Emphasis will be placed on simplicity of operation so that operation of the drive motors can be made an incidental task for the operators engaged in conducting the wind tunnel tests.

The automatic control and protective system will monitor the major drive system components and will initiate system shut down and annunciate cause of shut down for abnormal drive conditions.

3.2.2 Drive Alternate #2, Synchronous Motors Directly Coupled to Continuously Adjustable Pitch Fans and Provided with a Static, Thyristor, Rectifier-inverter System Sized for Adjustable Speed, Full Fan Pitch Operation at Tunnel Air Speeds Below 50 Percent of Rated Speed

This proposed system is similar in operation to Drive Alternate #1 above. The d-c motors of Alternate #1 are omitted, the synchronous motors are made full size and 15 percent capacity thyristor rectifier inverters are provided to cause the synchronous motors to perform the same adjustable speed functions as did the d-c motors of Alternate #1.

A synchronous motor has a shaft speed which is directly proportional to the frequency applied to its windings. To obtain adjustable speed operation of a synchronous motor, it is necessary to supply the motor with adjustable frequency electrical power. The advent of silicon-thyristors has made available a reliable, efficient and economical means for converting a-c from one frequency to another and in particular for converting constant frequency power to adjustable frequency power. Therefore it is proposed to use thyristor frequency conversion equipment to obtain adjustable speed operation of the synchronous motors.

To minimize the cost of the thyristor frequency conversion equipment, it is sized to be capable of performing the necessary function of starting and accelerating the associated synchronous motors to 60 Hertz with the fan blade pitch set at the fully depitched position. At 60 Hertz the motors will be synchronized and directly connected to the incoming power system and the frequency conversion equipment will be shut down. With the fan blades depitched, the motors require 15% of their rated overload power at 60 Hertz speed. This then dictates the rating of the static frequency conversion equipment.

With this size frequency conversion equipment, the synchronous motors can operate continuously as adjustable speed drives at shaft speeds below 50% of top rated speed because a fan requires only 1/8 of rated power when running at half speed and at full fan pitch.

Therefore the static frequency conversion equipment will be designed to operate the drive motors continuously at frequencies from 3 Hertz to 30 Hertz (5% to 50% of rated tunnel air velocity).

To minimize the cost of the inverters, line commutated inverters are proposed. These inverters obtain their commutating KVA from the synchronous motors that they serve rather from capacitor banks. The synchronous motor fields will be energized before the motors are to be started and will remain excited whenever the motors are running. The inverters will be artificially commutated when operating at very low frequencies by causing the rectifier to revert to its inverting mode whenever a current zero is required in the inverter. At higher frequencies, sufficient voltage will be generated by the rotation of the fully excited synchronous motor to cause the inverter to commutate in its normal manner as a line commutated inverter.

Because the synchronous motors always operate in synchronism with the inverter output frequency, including the standstill condition where the inverter is supplying d-c current, this method of starting is called synchronous starting.

Separate thyristor exciters will be provided for each synchronous motor field so that field current is available while the motor is at rest and so that field current can be regulated as desired during motor operation.

The rated inverter output voltage is half of the rated 60 Hz motor voltage. Hence the inverter can deliver its full rated output to the motors when the motors are operating at half of rated speed. As the motors are accelerated from 30 Hz to 60 Hz the motor field current will be weakened to maintain motor terminal voltage constant at the rating of the inverter. At a frequency slightly above 60 Hz, the inverter will be disconnected from the motors and the motor field currents will be raised to cause rated voltage to appear at the motor terminals. As the motors coast through synchronism with the 60 Hz utility system, they will be automatically connected to this system. After being connected to the 60 Hz system, the motors can be loaded by varying the pitch of the associated fan blades.

Table 3.2.2 below summarizes the ratings of the a-c motors and the rectifier-inverters.

TABLE 3.2.2

Fan	A	B	C
Total HP @ Max. Speed	24,000	24,000	24,000
A-C Synchronous Motor Data:			
Total Number Required	18	18	18
Continuous H.P.	19,200	19,200	19,200
2-Hour H.P.	24,000	24,000	24,000
60 Hz Synch. Speed (RPM)	133 1/3	156.52	240
Voltage	13,200	13,200	13,200
Frequency	60 Hz	60 Hz	60 Hz
Phases	3	3	3
Power Factor	1.0	1.0	1.0
Static Rectifier-Inverter Data:			
Total Number Required	3	3	3
Input			
Voltage	13,800 V	13,800 V	13,800 V
Phases	3 ∅	3 ∅	3 ∅
Frequency	60 Hz	60 Hz	60 Hz
Output			
30-60 Hz			
HP	21,600 HP	21,600 HP	21,600 HP
Voltage	6,900 V	6,900 V	6,900 V
3-30 Hz			
Volts/Hz	230 V/Hz	230 V/Hz	230 V/Hz
Phases	3	3	3

Figure 3.2.2 describes a proposed one-line diagram for a six motor drive sub-system. Three (3) identical sub-systems are required for the eighteen (18) fans.

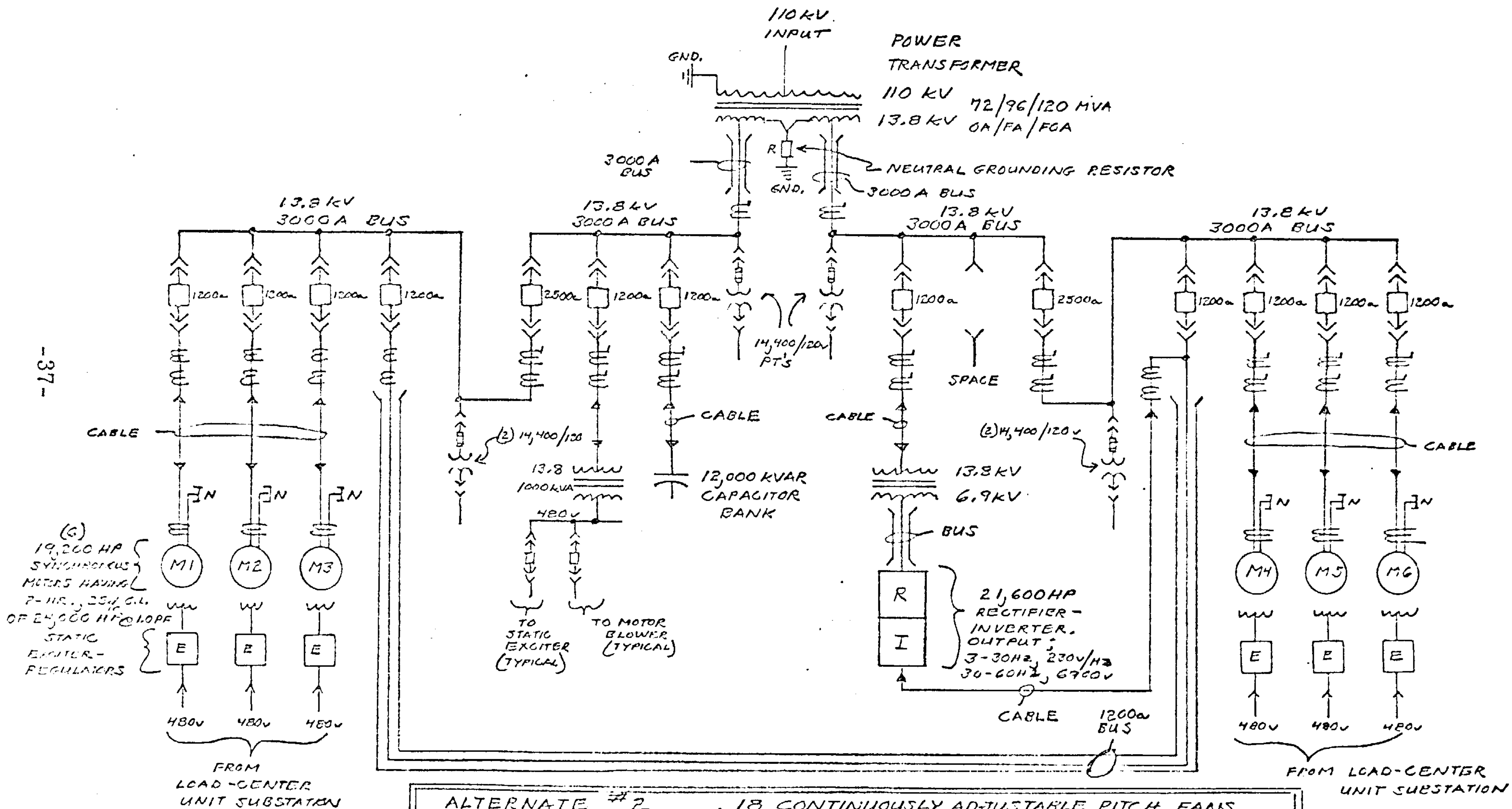
Looking at one six-motor sub-system (Figure 3.2.2), adjustable frequency operation is accomplished by opening the two 13.8 KV, 2500 ampere bus tie circuit breakers connecting to the main transformer secondary windings. The rectifier-inverter output is then connected to the two motor buses via the 1200 ampere breakers.

When synchronizing the main motors to the 60 Hz power line, the motors are accelerated to slightly above 60 Hz via the inverters, the inverters are disconnected from the motor buses and as the motors coast through synchronism the 2500 ampere bus tie circuit breakers are automatically closed.

After the main motors are connected to the power system, the tunnel air speed is adjusted by pitch control of the individual fans as described for system #1 above.

System power factor, during operation of the rectifier-inverters, is automatically regulated by switching the three 12 MVAR capacitor banks, one on each of the three main power transformers.

The capacitor switching transients will be suitably isolated from the static rectifier-inverters by virtue of their being connected to isolated windings on the main power transformers.



ALTERNATE #2, 18 CONTINUOUSLY ADJUSTABLE PITCH FANS
ONE-LINE DIAGRAM FOR MOTORS M1-M6
(TWO OTHER IDENTICAL SYSTEMS REQUIRED FOR M7-M12 AND M13-M18)
LARGE SCALE V/STOL WIND TUNNEL POWER SECTION DESIGN STUDY
FOR
NASA AMES RESEARCH CENTER, MOFFETT FIELD CALIFORNIA
100% SYNCHRONOUS MOTORS
150% THYRISTOR RECTIFIER INVERTERS

FIGURE 3.2.2

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M. D. Horton

System power factor during 60 Hz operation of the synchronous motors is regulated by controlling the synchronous motor field excitation.

This Alternate has one potential disadvantage, namely that parallel connected synchronous machines operating from a common power source, can exhibit inherent negative damping at certain operating speeds. This is usually most pronounced when operating at low electrical frequency and, if the proper design precautions have not been taken, can result in large power oscillations between machines. Similar oscillation phenomena have occurred between synchronous generating stations in electric utility systems operating at 60 Hz. These oscillations have been mitigated by the use of separate thyristor exciters for the synchronous generator fields and by the use of appropriate stabilizing and regulating circuits working into these independent exciters. The hardware required to implement this method of stabilization is included in the estimating prices tabulated in this report.

It is recommended that a comprehensive dynamic analysis of this six-machine sub-system be completed before a definite commitment is made to this system. The analysis should completely represent the synchronous motors, their excitation and regulating systems and the static frequency change via their differential equations. From this analysis, verification should be made that the system will operate stably over its starting and running speed ranges. Such a dynamic analysis is beyond the scope of this study. In view of the considerably saving in hardware cost afforded by this alternate and the possible application of this approach to other wind tunnel drives, the cost of such a dynamic analysis could be justified.

The proposed rectifier-inverter starting and speed control system has been successfully applied to single machines as shown in Reference #12. References 9-11 pertain to synchronous machine damping.

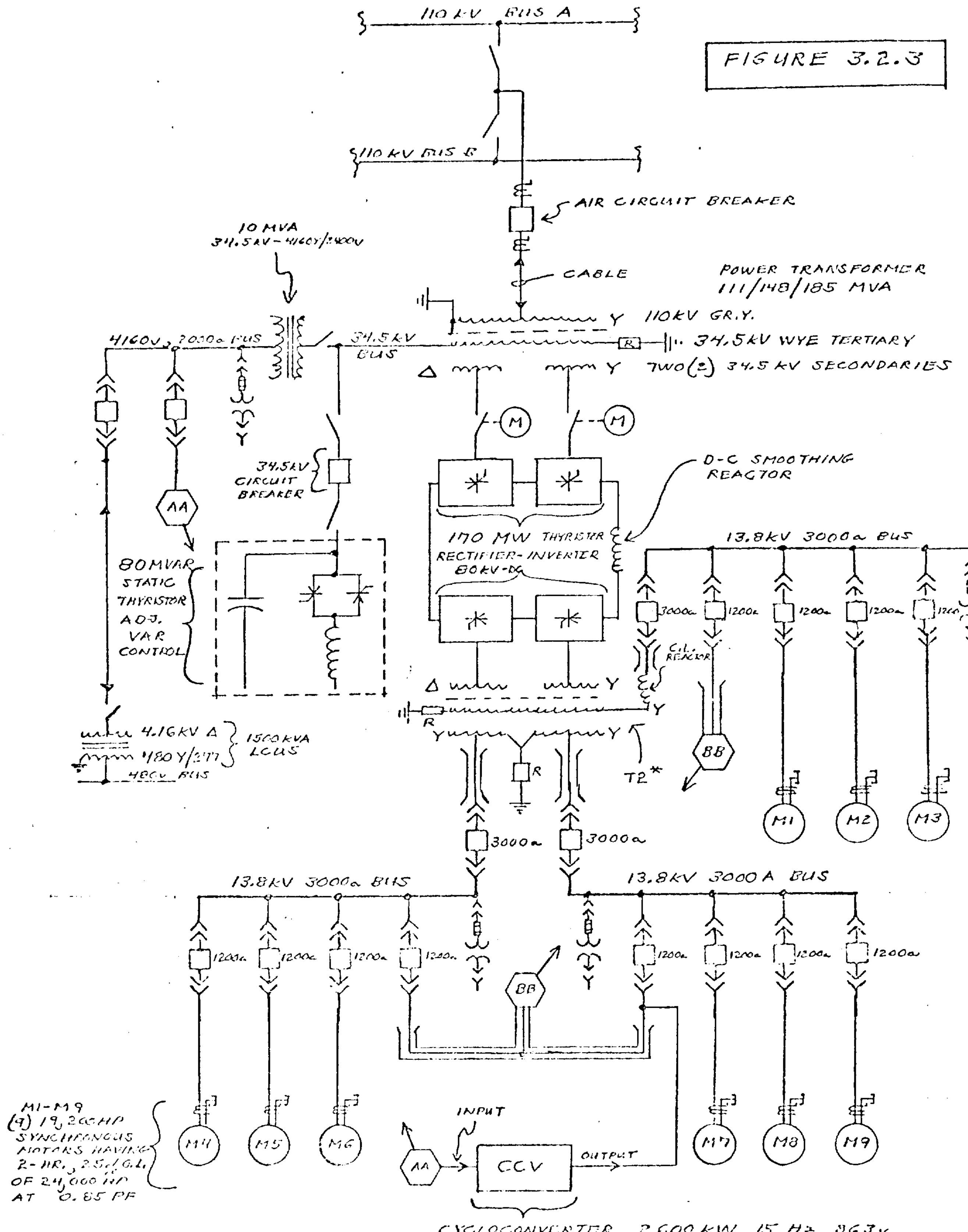
Multiple machine applications of this starting system have not yet been documented, however, there is a high probability that the multiple machine, inter-machine stability problem can be mitigated by appropriate independent control of the field excitation of the several synchronous machines.

3.2.3 Drive Alternate #3, Eighteen (18) Adjustable Speed Synchronous Motor Drives having Fixed Pitch Fans and Two (2) Static Thyristor Rectifier-Inverter Systems Each Serving Nine (9) Motors

This proposed electric drive system is similar in operation to Drive Alternate #2 above except the rectifier-inverter equipment is rated for the full speed, full power capability of the synchronous motors. In addition the motors and inverters will have a 1.125/1 constant horsepower adjustable speed range to maximize the air velocity attainable in the low speed tunnel leg.

Figure 3.2.3 is a power one-line diagram for one of the two subsystems proposed for this alternate. Two such systems would be required for the complete, 18 motor, 432,000 HP adjustable frequency wind tunnel drive system. This one-line assumes the frequency conversion equipment is to be used only for the subject drive.

FIGURE 3.2.3



* T2 = POWER TRANSFORMER
1- 34.5kV Δ PRIMARY
1- 34.5kV Y PRIMARY
1- 13.8kV Y TERTIARY
2- 13.8kV Y SECONDARIES

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M.D. Hutton

ALTERNATE #3, 18 FIXED-PITCH FANS
ONE-LINE DIAGRAM FOR MOTORS M1-M9
ONE IDENTICAL SYSTEM REQUIRED FOR M10-M18
LARGE SCALE V/STOL WIND TUNNEL POWER SECTION
FOR
NASA AMES RESEARCH CENTER, MOFFETT FIELD
100% SYNCHRONOUS MOTORS WITH RECTIFIER/INVERTER

The mechanical simplicity of a gearless electric motor driving a fixed pitch fan cannot be matched by any other fan-drive system. A few of its superior characteristics are tabulated below:

A. High Reliability

1. Simplicity of fixed pitch fan blade attachment permits designs, having lowest stresses at blade attachment point. This minimizes probability of mechanical failure at attachment point caused by steady-state or cyclic fatigue stresses.
2. Absence of moving parts within the hub eliminates possibility of wear and subsequent blade vibration and backlash.
3. Absence of moving parts within the hub eliminates need for lubrication of hub components.

B. Superior Air Flow Profile

The fixed pitch fan operating at adjustable speed inherently results in a more uniform air velocity profile from hub to tip of the fan than does an adjustable pitch, constant speed fan. The warp of the blade remains constant in an adjustable pitch fan as it changes its pitch. Hence reductions in air flow of adjustable pitch fans create a circulatory component of flow from hub to tip of the fan.

In a sub-sonic tunnel, this nonuniform air velocity from hub to tip of the fans can result in a undesirable air velocity variations at the wind tunnel test section.

C. Minimum Noise Power Level

The noise power produced by a fan is a function of its tip velocity. At 50% flow, the fixed pitch, adjustable speed fan experiences a 15 db reduction of noise as shown in table 5.2 of this report. The constant speed, adjustable pitch fan can be expected to create a constant maximum noise for all tunnel air flow conditions above 50% of rated tunnel air speed.

D. Highest Resolution of Air Flow Adjustment and Lowest Air Flow Drift with Time

The proposed adjustable speed electric drive systems will have modern solid-state digital speed regulators. The resolution of the speed setting function and the inherently low time drift of the precision crystal controlled reference frequencies make the adjustable speed fixed pitch fan systems superior to the adjustable pitch fan method of air flow adjustment. The latter has friction and backlash not present in the adjustable speed control systems and requires rotating mechanical and/or hydraulic and/or electrical connections to the rotating hub assembly.

3.2.3.1 Synchronous Motors

The proposed synchronous motors will be directly coupled to their associated fixed pitch fan. The motors will have a small (1.125/1) constant horsepower speed adjustment range in addition to the 20/1 speed adjustment range where load power varies as the cube of speed. The constant horsepower speed range allows operation to 146 Knots with the 133' x 200' test section and to 300 Knots with the 75' x 150' test section.

The motors will be rated as follows:

TABLE 3.2.3

SYNCHRONOUS MOTOR RATINGS FOR ALTERNATE #3

Fan	A	B	C
Number Required	18	18	18
Continuous HP	19,200 HP	19,200 HP	19,200 HP
2-Hour HP	24,000 HP	24,000 HP	24,000 HP
Constant HP Speed Range	133.3/150 RPM	156.5/176.1 RPM	240/270 RPM
Constant HP Freq. Range	60/67.5 Hz	60/67.5 Hz	60/67.5 Hz
Number of Poles	54	46	30
Voltage	13,200 V	13,200 V	13,200 V
Phases	3	3	3
Power Factor	0.85	0.85	0.85

3.2.3.2 Rectifier Inverters

It is proposed to employ two separate thyristor rectifier-inverters, each capable of driving nine (9) 24,000 HP synchronous motors.

Assuming a motor efficiency of 96%, the maximum total power requirement for nine motors is 166.1 MW.

Two thyristor frequency changer equipments, each rated 160 MW continuously, 176 MW for eight (8) hours, were placed in service in 1972 at the Eel River Station of the New Brunswick Electric Power Commission in Canada. These converters were manufactured by the Canadian General Electric Company using designs developed by the General Electric Company.

The Eel River converters have been operating in electric utility service for more than one year and have demonstrated that high reliability can be attained with thyristor frequency changer systems of this size.

The Eel River design has been used for the purposes of this study because its power rating almost exactly matches the rating required for the wind tunnel. Some design revisions would be necessary in the firing and snubber circuits for successful operation over the wide frequency and voltage range required for adjustable speed motor operation. However the basic power components and power circuits would remain unchanged.

To minimize the problems of motor starting and of motor stability at low operating speeds, it is proposed to furnish two 2600 KW starting cycloconverters, one for each group of nine motors. The cycloconverters would be used to start and synchronize to motors together and for adjustable speed drive operation between 5% and 25% of rated 60 cycle speed.

The rectifier inverters would be used for operation between 25% and 112.5% of rated 60 cycle speed. The cycloconverter method of starting is considered to be ideal for this application because so many motors are operating in parallel and because it minimizes the problem of discontinuous current in the high voltage rectifier-inverter bridges when operating at very low d-c current levels.

Consideration should also be given to the possible use of these large static frequency changers for other future wind tunnel drives on a shared time basis. The cost of the adjustable speed drives for the future tunnels would be greatly minimized if static adjustable frequency power was already available. This added flexibility could be attained by providing duplicate input/output transformers on the frequency changer system, thereby providing an adjustable frequency 110 KV system.

Transmission of the adjustable frequency power to other facilities could be at the 110 KV level. Transformers at the facility would transform the 110 KV down to the utilization voltage desired.

This approach also allows the adjustable frequency converters to be located remote from the wind tunnel and hence gives greater flexibility in selecting a suitable site layout.

There is considerable precedent within NASA for the use of large adjustable frequency power systems for a multiplicity of drives. Extensive installations, employing rotating machine frequency changer sets, are in existance at the Langley, Lewis and Ames Research Centers.

3.2.3.3 Static Power Factor Correction

It is proposed to provide power factor correction and harmonic filtering on a 34.5 KV tertiary winding of the main 60 Hz power transformer.

Station auxiliaries and the starting cycloconverter would also be fed from this tertiary winding.

The proposed static thyristor adjustable var control is another rather recent development employing power thyristors in high voltage series strings. The var control consists of a shunt capacitor bank, a shunt reactor and back-to-back thyristors in series with the reactor. Phase control of the thyristors causes a continuous variation in the effective reactance of the reactor and hence of the parallel capacitor/reactor circuit. If the reactor KVA equals the capacitor KVA, then the circuit vars can be continuously adjusted from zero to rated capacitor KVAR.

The capacitor bank will be sectionalized into several sections, each section having small series tuning reactors. By tuning capacitor sections to the 5th, 11th and 13th harmonics, the principal a-c harmonics of the rectifier and of the a-c thyristor reactance control will tend to flow thru this filter rather than in the 110 KV utility company lines. In this way, the harmonics present in the utility company lines will be reduced to acceptably low values. In addition to the tuned sections of the filter, an untuned section will also be provided to serve as a high frequency bypass.

3.2.4 Drive Alternate #4, Eighteen (18) Adjustable Speed Synchronous Motor Drives Having Fixed Pitch Fans, Each Motor Served by an Individual Thyristor Cycloconverter

Mechanically, the proposed system is identical to that of Alternate #3 above and has the same advantages when compared with constant speed adjustable pitch Alternates #1 and #2 above.

Electrically, this Alternate #3 is different in that it uses thyristor cycloconverters to convert 60 Hz constant frequency a-c to adjustable frequency a-c. The state of the art in cycloconverters has not yet matched the power ratings of thyristor rectifier-inverters proposed in Alternate #3 above. Therefore a separate cycloconverter is proposed for each of the 18 motors.

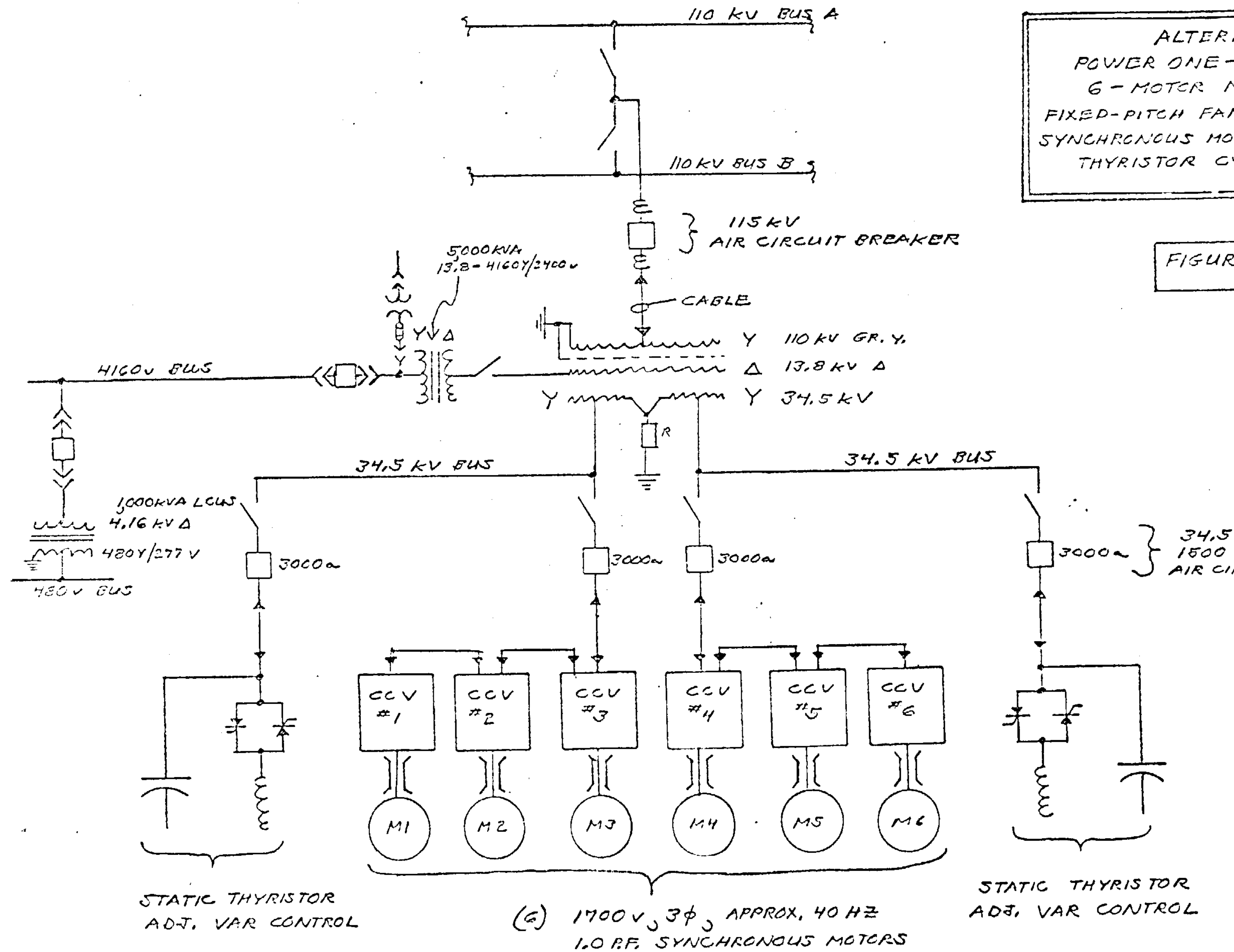
Figure 3.2.4 is a power one-line diagram of the proposed system.

3.2.4.1 Synchronous Motors

The synchronous motors for use with cycloconverters, operates at lower frequency and hence has fewer electrical poles for the same shaft speed. The state-of-the art thyristor cycloconverters have relatively low output voltages. The synchronous motor for use with a single cyclo-converter does not require an amortisseur winding nor does it have to have a lagging power factor rating (unity P.F. is adequate). This reduces the size and cost of the cycloconverter driven synchronous motor when compared with Alternate #3. The fact that the cycloconverter has to operate at a maximum frequency of approximately 40.0 Hz causes the

ALTERNATE #4
POWER ONE-LINE DIAGRAM
6-MOTOR MODULE
FIXED-PITCH FANS, ADJUSTABLE SPEED
SYNCHRONOUS MOTORS WITH
THYRISTOR CYCLOCONVERTERS

FIGURE 3.2.4



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M. D. Hatton

synchronous motors to go up in size, however, the overall size and cost of the 40 Hz unity power factor synchronous without an amortisseur winding is less than that of a 60 Hz, 0.85 PF motor with amortisseur winding.

The motors will be rated as follows:

TABLE 3.2.4

SYNCHRONOUS MOTOR RATINGS FOR ALTERNATE #4

Fan	A	B	C
Number Required	18	18	18
Continuous H.P.	19,200 HP	19,200 HP	19,200 HP
2-Hour H.P.	24,000 HP	24,000 HP	24,000 HP
Constant H.P. Speed Range	133.3/150 RPM	156.5/176.1 RPM	240/270 RPM
Constant H.P. Frequency Range	35.5/40 HZ	36.5/41.1 HZ	36/40.5 HZ
Number of Poles	32	28	18
Voltage	1700 V	1700 V	1700 V
Phases	3	3	3
Power Factor	1.0	1.0	1.0

3.2.4.2 Cycloconverters

The eighteen, twelve-pulse thyristor cycloconverters will each have individual transformers to operate from a 34.5 KV, 3 phase, 60 Hz power system. The cycloconverter output frequency will be adjustable from zero to 1700 volts. The cycloconverter output power rating will be 14,920 KW continuously and 18,650 KW for two hours at an output power factor of unity.

Thyristor cycloconverters have been built in multi-thousand kilowatt sizes. The power circuit components of the thyristor cycloconverter are similar to those widely employed for a-c to d-c power conversion for adjustable speed d-c drives. Cycloconverters of the size required for this application are well within the state of the art if the 3-phase line-to-line output voltage is limited approximately 2 KV. While higher output voltage thyristor cycloconverters can and will undoubtedly be developed, the already developed lower voltage cycloconverters are used for the purposes of this estimate.

3.2.4.3 Power Factor Correction

The power factor of the input circuit of a cycloconverter is inherently quite low (0.6-0.7 lagging at full load). It is proposed to correct the power factor and filter the major cycloconverter a-c line harmonics via static var controls of the same type described in detail in paragraph 3.2.3.3 above.

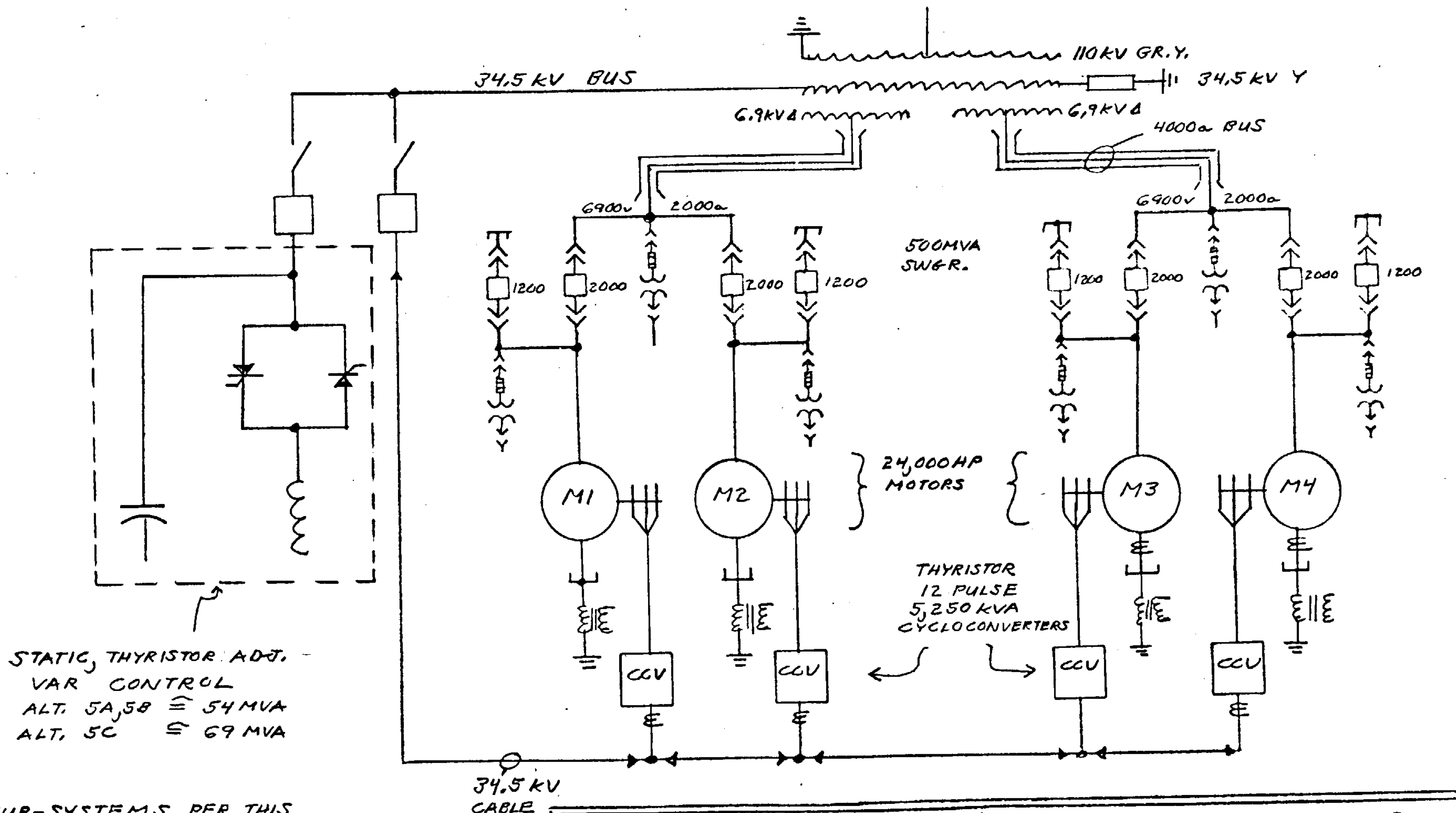
3.2.5 Drive Alternate #5, Eighteen (18) Adjustable Speed, Geared, Doubly-fed, Wound Rotor Induction Motor Drives with Thyristor Cycloconverters and Fixed Pitch Fans

The proposed electric drive system consists of 18 drives, each consisting of an adjustable speed wound rotor induction motor, geared to a fixed pitch fan. Direct drive wound rotor induction motors at these low speeds and high horsepowers are not considered to be a good economic or engineering choice.

Figure 3.2.5 is the power one-line diagram for this system.

The motors are started and operated at frequencies up to 40 Hertz as single-fed squirrel cage induction motors. The stators are shorted via starting breakers and act as squirrel cage motor secondary windings. The cycloconverters supply adjustable frequency power to the rotor windings which are acting as motor primaries.

At 40 Hertz, a transition is made from singly-fed to doubly-fed motor operation. The cycloconverter output voltage is removed, the stator shorting breaker is opened and cycloconverter power is reapplied at cycloconverter frequency of 20 Hertz and a cycloconverter output phase sequence opposite to that employed during singly-fed operation. The motor shaft is rotating at 40 Hz speed, the 20 Hz rotor excitation adds to this to cause an induced voltage in the stator winding of 60 Hz. The controls automatically adjust the frequency, phase and amplitude of the cycloconverter output such that the stator winding induced voltage is synchronized in magnitude, phase and frequency to the 60 Hz a-c line.. The stator circuit breaker then closes. This transition from singly-fed to doubly-fed takes only a fraction of a second to complete.



NOTE.
4- SUB-SYSTEMS PER THIS SKETCH FOR 16 MOTORS TOTAL
1-1/2 SUB-SYSTEM WITH SINGLE-SECONDARY TRANSFORMER FOR REMAINING 2 MOTORS

ALTERNATE #5, 18 FIXED PITCH FANS
DOUBLY-FED WOUND-ROTOR INDUCTION MOTORS WITH
THYRISTOR CYCLOCONVERTERS AND STATIC ADJ. VAR CONTROL
LARGE SCALE V/STOL WIND TUNNEL POWER SECTION
FOR
NASA AMES RESEARCH CENTER, MOFFETT FIELD, CALIF.

FIGURE 3.2.5

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When operating doubly-fed, the cycloconverter frequency and amplitude can be adjusted to cause the main motor to operate at any desired speed between 20 Hertz below synchronous speed to 20 Hertz above synchronous speed. At 20 Hertz above synchronous speed, the 10 pole induction motors will be operating at 960 RPM.

At top speed, the cycloconverter supplies 25% of the motor shaft power via the motor rotor winding and the 60 Hertz power line supplies 75% of the motor shaft power via the motor stator winding.

This type of motor then requires only 25% of the cycloconverter capacity required by the synchronous motor cycloconverter drive described in Alternate #4 above. However, as will be shown later, the induction motor is a more costly motor than a synchronous motor and tends to offset the saving in cycloconverter rating.

3.2.5.1 Wound Rotor Induction Motors

The proposed wound rotor induction motors have ten (10) poles and operate at a top rated speed of 960 RPM. They will be similar in construction to the four motors driving the ARC Unitary Tunnel except they will be approximately half the horsepower rating. (The Unitary Tunnel motors are each rated 45,000 HP continuously and 54,000 HP for one hour).

The proposed motor rating is summarized in Table 3.2.5 below.

TABLE 3.2.5

MOTOR AND CYCLOCONVERTER RATINGS
ALTERNATE #5

Number of Drives	18
A-C Induction Motor Data:	
Continuous H. P.	19,200/19,200 H. P.
2-Hour H. P.	24,000/24,000 H. P.
Number of Poles	10
Rated Speed	853.3/960 RPM
Rated Frequency:	
Stator	60 Hz
Rotor	11.1/20 Hz
Stator Voltage	6,600 Volts
Locked-Rotor Voltage	4,200 Volts (approx.)
Stator Phases	3
Rotor Phases	3
Cycloconverter Data:	
Output:	
Line-to-line RMS Voltage	1,400 Volts
Phases	3
Pulses Per Incoming A-C Cycle	12
KW	5,250 KW
Power Factor	1.0
Frequency	40 Hz
Input:	
Voltage	34,500 Volts
Phases	3
Frequency	60 Hz

3.2.5.2 Cycloconverters

Eighteen (18) thyristor cycloconverters are required, one for each motor. The ratings are tabulated in Table 3.2.5 above.

This rating of cycloconverter has been built for other similar applications and hence presents no state-of-the-art design problems.

3.2.5.3 Gears

The proposed speed reduction gearing is similar in power and speed ratings to marine reduction gearing widely used for ship propulsion.

Three different gear alternates are required for the fan alternates A, B and C. Each alternate will be sized for a small (1.125/1) operating speed range at constant horsepower rating to maximize the air velocity attainable on the low speed wind tunnel leg.

The gearing will be rated as tabulated in Table 3.2.5.3 below:

TABLE 3.2.5.3

GEAR RATINGS, ALTERNATE #5

Fan	A	B	B
Quantity	18	18	18
Horsepower Per Fan	24,000/24,000	24,000/24,000	24,000/24,000
Gear Ratio	960/150 RPM	960/176.1 RPM	960/270 RPM
Constant Horsepower Output Speed Range	133.1/150 RPM	156.6/176.1 RPM	240/270 RPM
Horsepower to Vary As Cube of Speed			
When Operating Below Constant HP Speed Range			
Non-reversible Torque and Speed			
Service Factor	1.0	1.0	1.0

3.2.6 Alternate #6, Eighteen Drives Each Consisting of a Gas Turbine Mechanically Coupled to a Fixed Pitch Fan and a 10% Direct-Current Electric Motor for Low Speed Operation and for Vernier Speed Control

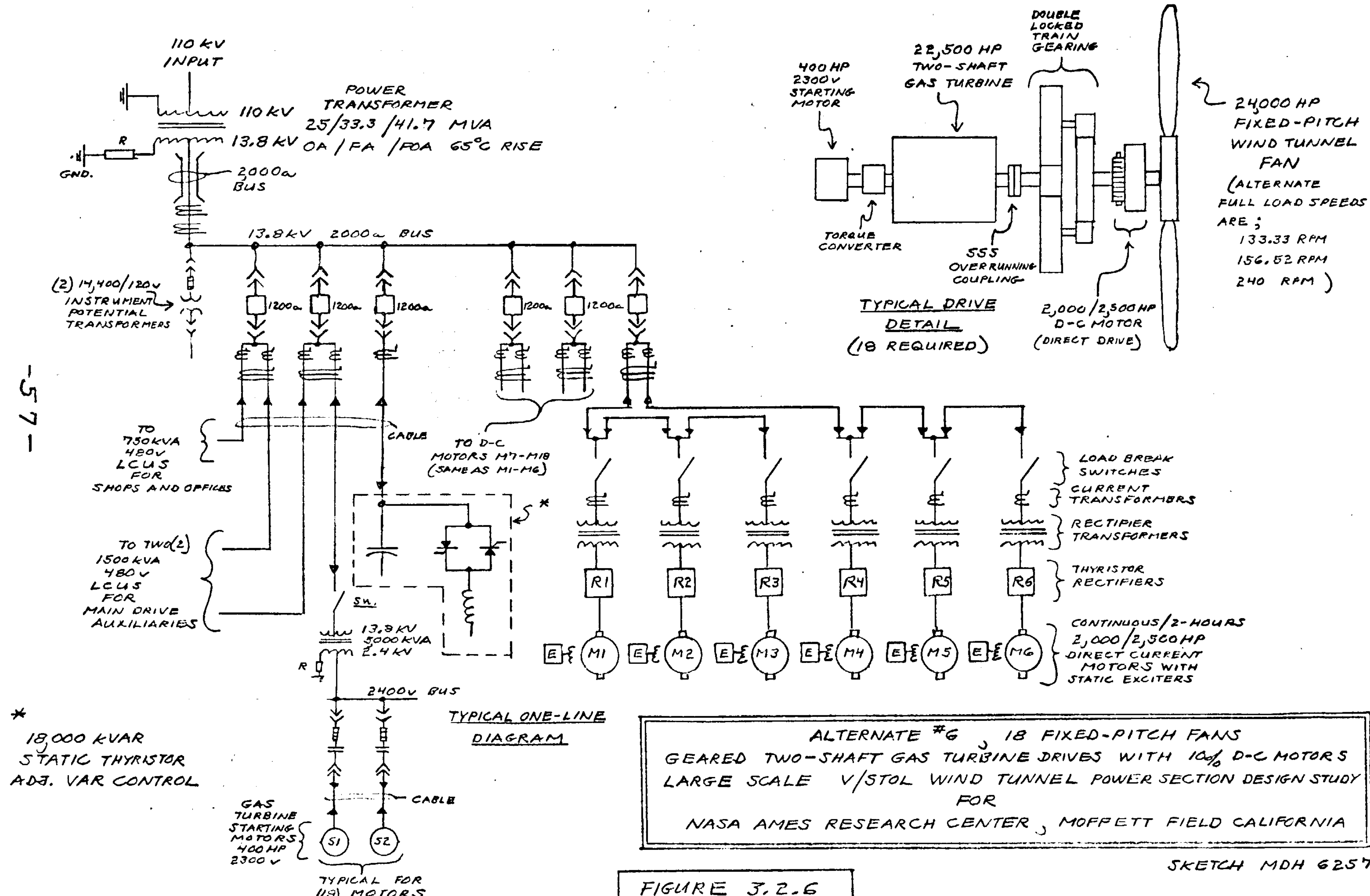
A one line diagram of the proposed system is shown in Figure 3.2.6.

The proposed system consists of a two shaft gas turbine driving a speed reduction gear through a self-disengaging shaft coupling. The low speed gear output drives the fan through a 10% capacity direct current motor.

The direct current motor is capable of driving the fan at all speeds up to approximately 45% of top rated fan speed. During this operation, the gas turbine is not running and the self-disengaging shaft coupling in the gas turbine output shaft prevents windmilling of the turbine.

For operation above 45% speed, the gas turbines are started. As their power turbine reaches the operating speed of the gear pinion, the self-disengaging shaft coupling will automatically engage. The power of the gas turbine will then augment that of the d-c motor. The d-c motor will be regulating speed, so its power can go to zero or to its rated power regenerating (electrical power being sent back into the 60 Hz power line) if this is necessary to hold the fan speed to 45% when the gas generator turbine-compressor unit is running at its lowest practical idling speed.

As more fan speed is required, the d-c motor will be employed to precisely regulate the set speed, however, it will be helped by the gas turbine unit. The gas turbine governor will automatically operate to hold the d-c motor armature current to a preselected constant value within the current rating (motoring or regenerating) of the d-c motor.



* 18,000 KVAR STATIC THYRISTOR ADJ. VAR CONTROL

ALTERNATE #6, 18 FIXED-PITCH FANS
GEARED TWO-SHAFT GAS TURBINE DRIVES WITH 10% D-C MOTORS
LARGE SCALE V/STOL WIND TUNNEL POWER SECTION DESIGN STUDY
FOR
NASA AMES RESEARCH CENTER, MOFFETT FIELD CALIFORNIA

SKETCH MDH 62573-1

FIGURE 3.2.6

M. D. Harten

By teaming the gas turbine with a small capacity d-c drive, gas turbine operation at low speed, where the efficiency is poor, is minimized. Also, a gas turbine alone is incapable of regulating precise speed over output speed ranges of 20 to 1 when the output load is a fan. The addition of the 10% capacity d-c motor allows for precise speed control in this low speed region where the gas turbine is grossly inefficient and where the gas turbine has poor governing characteristics.

Should the electric power system at the wind tunnel site be incapable of serving these 10% capacity d-c motors, a separate gas turbine packaged power plant could be installed to provide the necessary electric power. This would then make the tunnel drive 100% gas turbine.

The proposed two-shaft gas turbines are capable of constant horsepower operation over a 1.125/1 speed range near top rated speed. Hence two position wind tunnel fans are unnecessary to meet the flow requirements of the two test legs. Accordingly we are proposing fixed pitch fans for this application.

3.2.6.1 Gas Turbines

The fan power requirement is 24,000 HP at rated speed for periods as long as two hours. It must be capable of 19,200 HP continuously. This would allow continuous operation of all wind tunnel air speeds below 92.8% of maximum rated air speed.

Allowing 4% for gearing loss, the gas turbines must deliver a peak power of 25,000 HP if the d-c motor is operating at zero current. If the d-c motors remain fully loaded, the gas turbine need only deliver 22,500 HP maximum. Hence any two-shaft gas turbine having a rating between 22,500 HP and 25,000 HP could be applied.

Heavy duty industrial gas turbines and aircraft derivative gas turbines are both available in this horsepower range. Recent competitive bidding at NASA Lewis Research Center indicates close price competition between the two types of gas turbines in the horsepower ratings required for this job (the heavy duty industrial gas turbines were evaluated as low bidder). Hence, the heavy duty industrial gas turbines were used for the subject study.

Full load speed for the turbines output shaft is 4,670 RPM.

The standard electric motor starting will be employed for the gas turbines. This consists of a 400 horsepower squirrel cage induction motor and a hydraulic torque converter for each of the 18 gas turbines.

Gas turbines can be operated on natural gas, natural gases of low methane content, gases other than natural gas, low BTU coal gas, distillate oil, naptha, residual oil, crude oil, or other fuels meeting General Electric Gas Turbine Products Division specifications. They also are available for dual fuel operation with various combinations of fuels. For the purposes of this study, operation on distillate oil is assumed.

3.2.6.2 Speed Reduction Gearing

The proposed speed reduction gearing is similar in power and speed ratings to marine reduction gearing widely used for ship propulsion.

Three different gear alternates are required for the fan alternates A, B and C. Each alternate will be sized for a small (1.125/1) operating speed range at constant horsepower rating to maximize the air velocity attainable on the low speed wind tunnel leg.

The gearing will be rated as tabulated in Table 3.2.6.2 below:

TABLE 3.2.6.2

GEAR RATINGS, ALTERNATE #6

Fan	A	B	C
Quantity	18	18	18
Horsepower Per Fan	24/24 KHP	24/24 KHP	24/24 KHP
Gear Ratio	4670/150 RPM	4670/176.1 RPM	4670/270 RPM
Constant HP Output Speed Range	133.1/150 RPM	156.5/176.1 RPM	240/270 RPM
Horsepower to Vary as Cube of Speed When Operating Below Constant HP Speed Range			
Non-reversible Torque and Speed			
Service Factor	1.0	1.0	1.0

3.2.6.3 D-C Motors

The proposed direct current motors will each be rated to carry the full load through-torque of the geared gas turbine prime mover. The d-c motor ratings are tabulated in Table 3.2.6.3 below:

TABLE 3.2.6.3

D-C MOTOR RATINGS FOR ALTERNATE #6

Fan	A	B	C
Quantity	18	18	18
Continuous HP	2,000 HP	2,000 HP	2,000 HP
2-Hour Overload HP	2,500 HP	2,500 HP	2,500 HP
Base Speed	57.2 RPM	67.1 RPM	103.2 RPM
Top Speed	150 RPM	176.1 RPM	270 RPM
Voltage	700 Volts	700 Volts	700 Volts

3.2.6.4 Thyristor Rectifiers and Power Factor Correction

Eighteen individual thyristor rectifiers will be employed to service the eighteen d-c starting motors.

Power factor correction will be obtained by a static adjustable var control system.

The vars will be controlled via back-to-back thyristors operating in series with a shunt reactor. Fixed tuned capacitors operating in parallel with the shunt reactors allow the combination of capacitor reactor and thyristors to be smoothly adjusted over a range of vars from zero to rated capacitor KVAR.

The capacitors are also provided with tuning chokes which cause them to serve a second function of filtering harmonics from the power system.

4. CONTINUOUSLY VARIABLE PITCH FANS

To comply with paragraph D of the work statement, the General Electric Company solicited bids for an engineering study of variable pitch fans from four vendors who had previously submitted fan cost estimates for contract Reference 4.

WARCO

Parsons

Allis Chalmers

Dominion Engineering

The work statement for this subcontract follows:

> The vendor performing this study shall provide the following information.
>
> 1. Cost - The influence of the following variables on hub cost shall be reported:
>   a. Blade tip speeds of 300, 400, 500, 600 ft/sec
>   b. Blade numbers 5, 10, 15, 20
>   c. Hub diameter 15 ft., 20 ft., 25 ft., where the ratio of blade to hub diameter is about .45
>
> 2. Feasibility - The methods of manufacturing, balancing, assembly, shipment, erection, control, instrumentation, lubrication and maintenance shall be considered and the means of assuring successful completion of these functions discussed in the report. Any operations requiring new development for this job should receive special attention.
>
> 3. Reliability - The general stress levels of material, bearing loads, control functions, fault detection and repair, balance requirements, and failure modes should be considered. Critical items if any should be identified in the report.

4. Operational Characteristics - The blade tracking requirements, starting conditions, pitch range, rate of pitch change, blade loads during pitch change, and requirements of pitch readout and control will be supplied the vendor by the General Electric Company. The vendor will evaluate these requirements and report on the ability of the proposed design to meet specifications.

5. Life and Integrity - The anticipated life of wearing components, and service requirements, should be considered.

The WARCO Company of Agawam, Massachusetts (Div. of Albany International Corporation) was the successful bidder.

Our intent in this subcontract was to provide cost and feasibility inputs which could more accurately assess the influence blade number and fan diameter. For this purpose, we supplied WARCO with the geometry and blade forces and moments for four fan designs from the previous contracted study, Reference 4 . The fan geometric parameters are given in Table 4.1 and pertinent force data is included in WARCO's technical report which is included as part of this submittal. From Table 4.1, it can be noted that fans were selected at 40 and 53 ft. diameter at from 7 to 21 rotor blades. This covers the complete range of possibility considered in the previous studies.

4.1 Blade Root Pitching Moment

Since the pitch of the blades are adjustable, consideration was given to the pitch forces over the entire range of synchronous speed operation from zero tunnel flow to the larger test section maximum flow.

Airfoils typical of fan application such as the Clark Y or 2300 series have remarkably invarient moment coefficient. This is illustrated in Figure 4.1 where data over a range of angle of attack from -13.5^{o} to $+5^{o}$ angle of attack is seen to have an invarient moment coefficient about the quarter chord point. Thus no moment reverse would be experienced even with the blade tip sections depitched so as to pump in the reverse flow direction. The actual root moments are then just proportional to the dynamic pressure of the relative velocity vector.

As discussed in Reference 4, the 2300 series of airfoils is favored and these foils have a moment coefficient of about -.040 over the range of available data from -4^{o} angle of attack to stall. Further as with the Clark Y, we do not anticipate any change up to negative stall. Using this coefficient the minimum moment of the four fans over the range of flows and at synchronous rpm's is given in Table 4.2. Further, since the most forward location of the center of pressure of the 2300 series of blades is 27% of the blade chord from the leading edge, it is recommended that the blade pivots be at the 25% chord point.

Fan 5 because of the high tip speed would have the highest blade pitching moments. The moment and blade angle vs. flow is given in Figure 4.2 for fan 5 and in Figure 4.3 for fan 4. The blade angle variation for fan 4 is also typical for fan 11A. Fan 9A angle vs. flow would be intermediate between fans 4 and 5.

4.2 Motor Synchronization

The starting motors, DC or variable frequency power, are specified as having 15% of the full load power and thus 15% of the full load torque at synchronous speed. Reducing torque to this low value requires depitching the fan. Figures 4.4 and 4.5 illustrate the conditions for the two tunnel sections for fan 11A.

At 15% torque, the fans would be limited to between 30% and 35% maximum flow and require a depitch of 26° from their respective operating condition.

4.3 Variable Pitch Fan Study

The WARCO design and cost study is included herein as an attachment. Using the costs from this study, the fan cost comparisons of Reference 4 were updated as given in Table 4.3.

Table 4.1

FAN GEOMETRIC DATA AND OPERATING PARAMETERS

Configuration / Parameter	#4	#5	#9A	#11A
Number of Fans	18	18	20	20
Tip Diameter Ft.	53.0	53.0	40	40
Hub Diameter Ft.	26.5	23.85	20	20
Hub Diameter Ratio	0.50	0.45	0.50	0.50
Number of Blades	16	7	16	21
Rotating Speed RPM	150	225	244	189
Tip Speed Ft/Sec	416	624	511	396
Blade Length Ft.	13.25	14.57	10.00	10.00
Hub Chord Ft.	4.90	5.40	3.53	4.20
Pitch Chord Ft.	4.16	4.30	2.99	4.20
Tip Chord Ft.	3.42	3.20	2.45	3.08
Blade Twist Degrees	23.37	19.2	22.6	30.1

TABLE 4.2

MINIMUM STEADY BLADE PITCHING MOMENT

AT BLADE ROOT

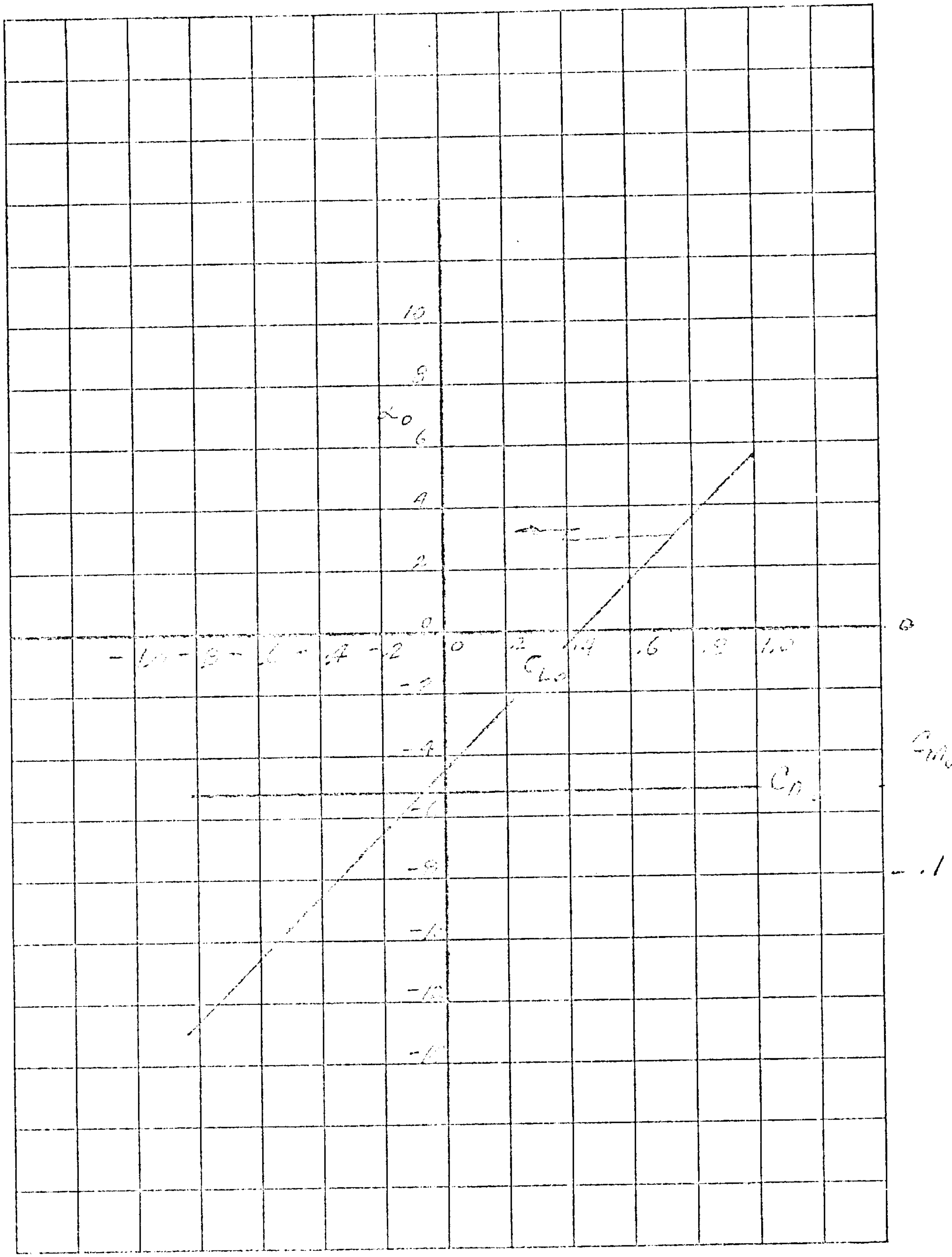
Fan	Tunnel Flow		
	0	300 K	150K Y Leg
4	985 ft lbs	1250 ft lbs	1496 ft lbs
5	2070 ftllbs	2328 ft lbs	2547 ft lbs
9A	583 ft lbs	722 ft lbs	916 ft lbs
11A	525 ft lbs	735 ft lbs	1021 ft lbs

TABLE 4.3 - FAN COSTS

Re: Fans Table 2-1, Reference 4

Remarks	Fan 1	Fan 2	Fan 3	Fan 4	Fan 5	Fan 6	Fan 7	Fan 8	Fan 9	Fan 10	Fan 11	Fan 12
No. of Blades	19	16	7	16	7	16	16	11	21	16	16	11
Fan Diameter	44.8	53	53	53	53	47	47	47	40	40	40	40
Total Rotor Mfg. Cost	430,371	392,610	323,095	541,645	419,200	362,418	493,373	371,190	392,905	332,225	445,110	341,714
Total Stator Mfg. Cost	107,418	107,418	107,418	107,418	107,418	90,376	90,376	90,376	73,216	73,216	73,216	73,216
Total Mfg. Cost/Fan	537,789	500,028	430,573	649,063	525,618	452,794	583,749	461,566	466,121	405,441	518,326	414,930
No. of Fans	18	18	18	18	18	20	20	20	20	20	20	20
Total Mfg. Cost	9,680,202	9,000,504	7,749,234	11,683,134	9,461,124	9,055,080	11,674,980	9,231,320	9,322,420	8,108,820	10,366,520	8,298,600
Rotor Tooling	172,430	186,860	201,500	208,360	222,250	172,430	190,530	190,530	165,875	158,000	158,000	153,000
Stator Tooling	20,000	20,000	20,000	20,000	20,000	18,000	18,000	18,000	15,000	15,000	15,000	15,000
Engineering	300,000	275,000	275,000	450,000	450,000	300,000	475,000	475,000	300,000	300,000	475,000	475,000
Transportation & Erection	234,000	234,000	234,000	306,000	306,000	260,000	340,000	340,000	260,000	260,000	340,000	340,000
Total Fan Cost	10,406,632	9,716,364	8,479,434	12,667,494	10,459,374	9,805,510	12,708,510	10,254,850	10,063,295	8,841,820	11,354,520	9,286,600

CLARK Y MOMENT AND LIFT
VS.
ANGLE OF ATTACK



"Moment about 1/4 chord positive clockwise"

FIGURE 4.1

TOTAL BLADE ROOT PITCHING MOMENT
ABOUT 25% CHORD FROM L.E. FAN #5
AT 100% RPM

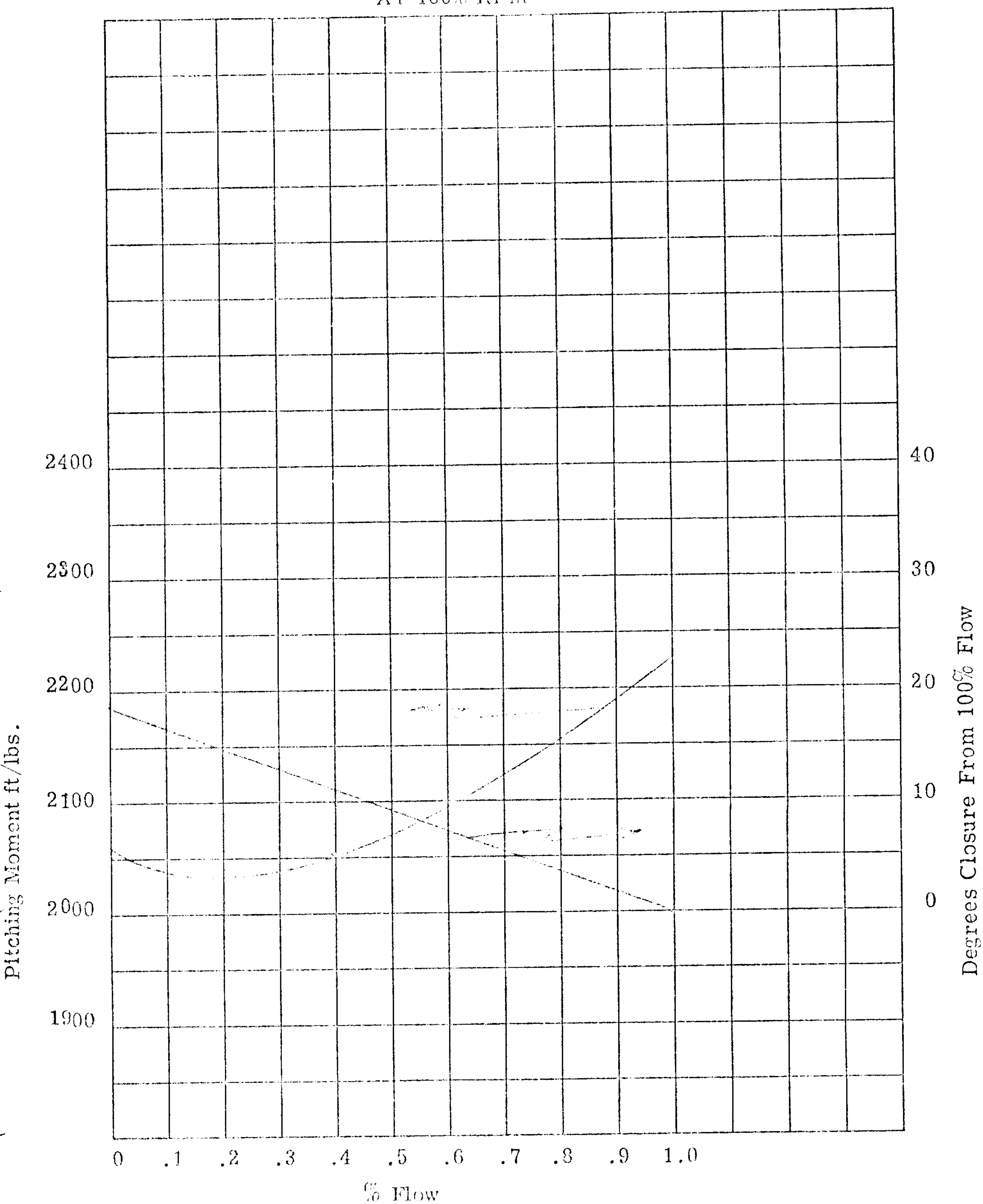


FIGURE 4.2

TOTAL BLADE ROOT PITCHING MOMENT
ABOUT 25% CHORD FROM L.E. FAN #4
AT 100% RPM

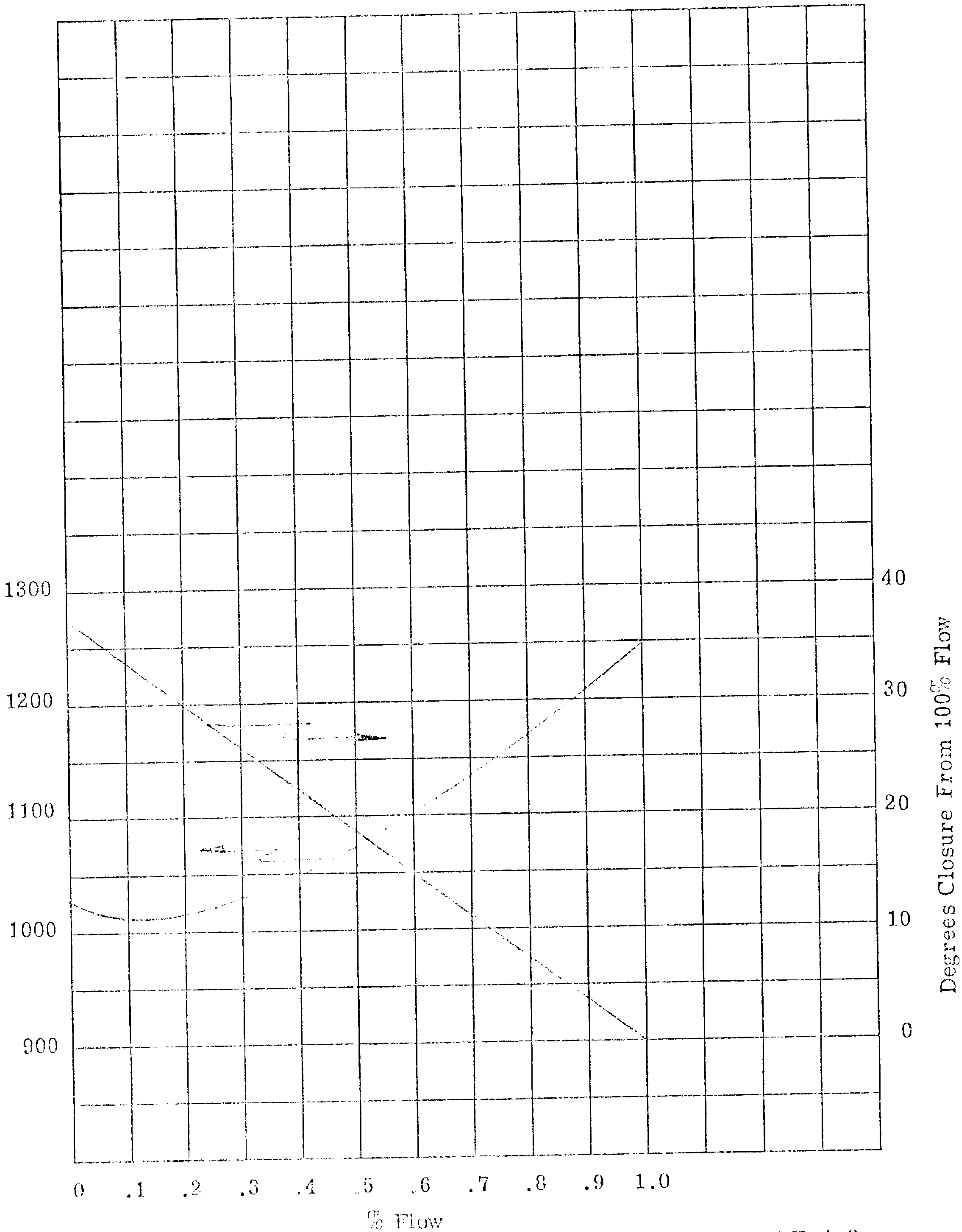
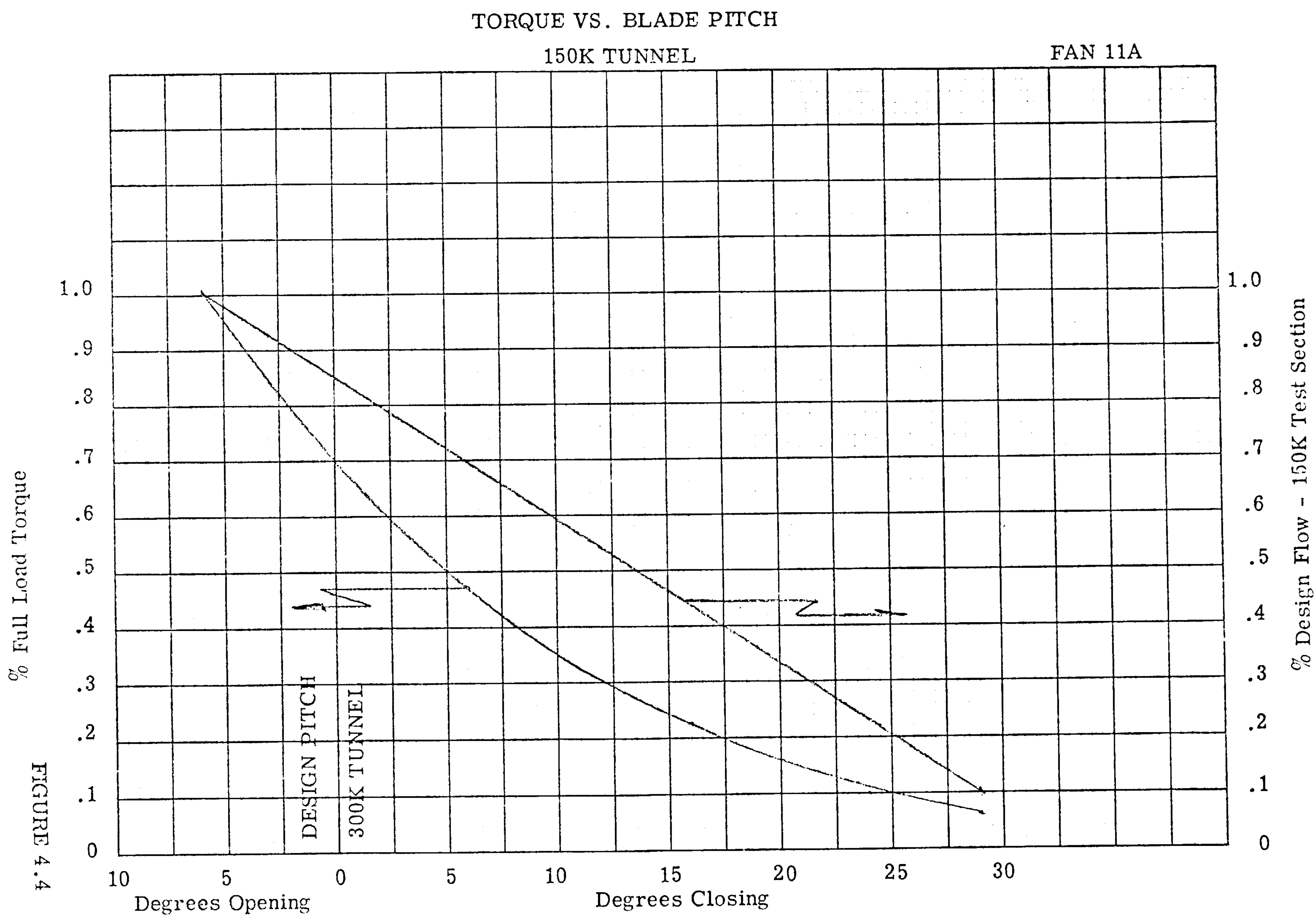


FIGURE 4.3



TORQUE VS. BLADE PITCH
150K TUNNEL
FAN 11A
% Full Load Torque
% Design Flow - 150K Test Section
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
DESIGN PITCH
300K TUNNEL
10
5
0
5
10
15
20
25
30
Degrees Opening
Degrees Closing

FIGURE 4.4

TORQUE VS. BLADE PITCH

300K TUNNEL

FAN 11A

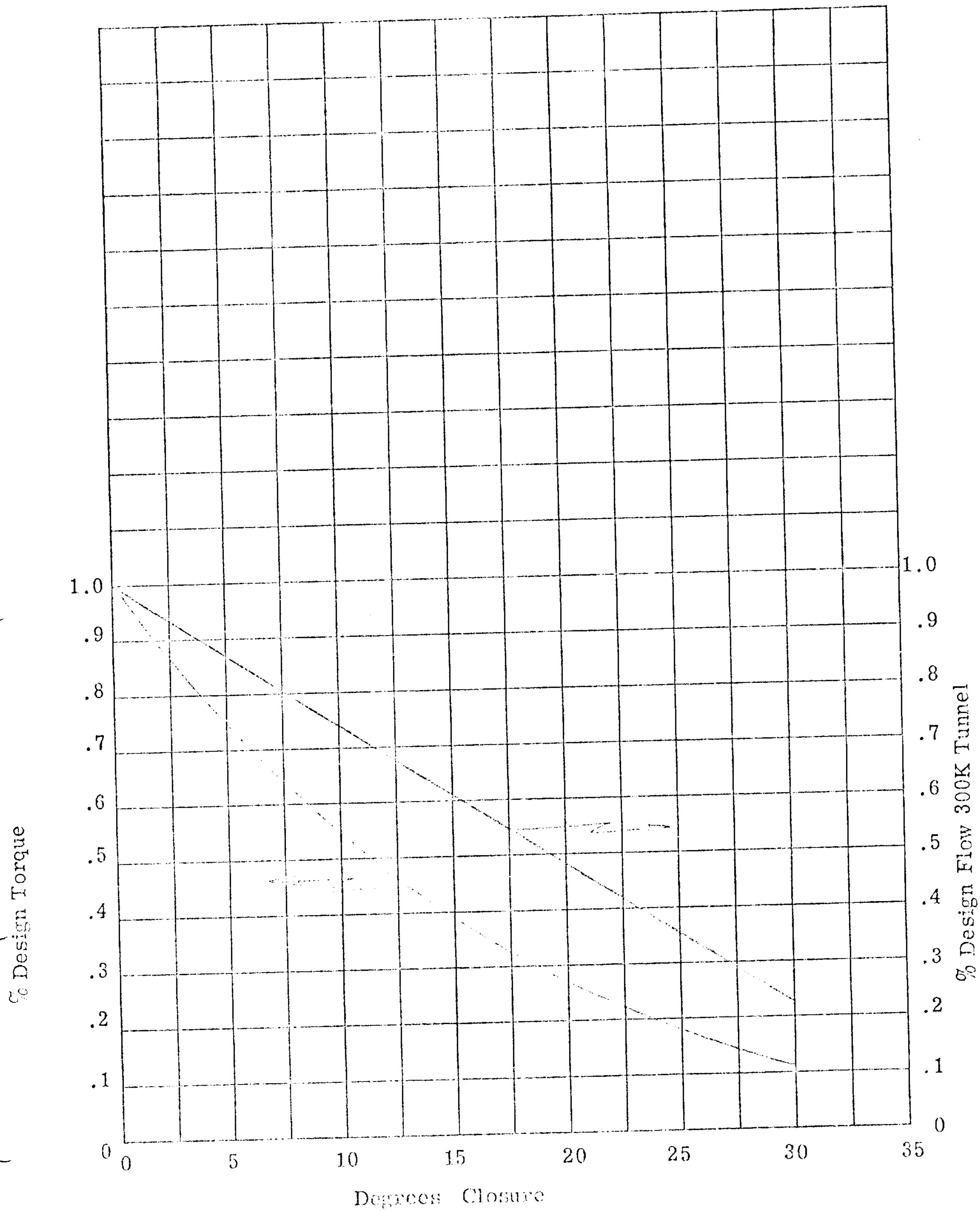


FIGURE 4.5

5. SOUND POWER ESTIMATES

The total sound power radiated from 18 fans is estimated based on the methods of Graham and Parker, References 7 and 8. The results are given in Table 5-1 where it can be noted the 350 ft/sec tip speed fan is about 13 db quieter than the 630 ft/sec fans.

Variable pitch fans would operate at maximum rpm from 100% to about 50% test section velocity. The sound power output would stay approximately constant over this entire range of velocities. However, at 50% flow the fans could also operate at half synchronous rpm and design pitch, which would result in about a 15 db reduction in noise as shown in Table 5.2. As the sound power is assumed proportionate to the 5.5 power of the rpm further reductions in rpm are continuously beneficial.

5.1 Gas Turbine Operation

With 18 gas turbines driving the fans rather than electric motors an additional significant noise source is introduced. It would be necessary to silence both the intake and exhaust and to package the turbine to attenuate the casing radiated noise. Adequately silenced however, the gas turbine could be made as quiet or quieter than the 350 ft/sec tip speed fan running at half speed.

A comparison of the sound power radiated from a single 350 ft/sec fan operating at half design speed, with that of a single General Electric

MS 5000 industrial service gas turbine is indicated in Table 5.3. The sound power radiated from the compressor intake and from the turbine enclosure is given separately from the sound power radiated from the turbine exhaust. With a more conventional baffle silencer, the latter is the dominant noise offender. However, if the more modern switchback silencer were used, the exhaust noise is insignificant compared to the fan or package noise at all but the lowest frequency band.

TABLE 5.1

ESTIMATED SOUND POWER LEVELS
OF POSSIBLE FANS FOR 75 x 150
FOOT TUNNEL (18 fans, 50 foot tip
diameter, H/D = .5) AT NORMAL
SPEEDS AS INDICATED

Tip Speed ft/sec	350.00	410.00	628.00
RPM	133.33	156.52	240.00
Octave Band		Sound Power Levels re 10^{-13} watts	
3.9	152.3	155.1	162.5
7.8	155.1	158	165.5
15.6	157.5	160.5	168.3
31.2	158.8	162.1	170.6
62.5	158.1	161.9	171.5
125	155.9	160	170.6
250	153.1	157.3	168.3
500	150.2	154.3	165.4
1,000	147.2	151.4	162.5
2,000	144.2	148.4	159.5
4,000	141.2	145.3	156.5
8,000	138.2	142.3	153.5
16,000	135.1	139.3	150.5
OVERALL	165.1	168.6	178.0

TABLE 5.2

ESTIMATED SOUND POWER LEVEL OF POSSIBLE FANS FOR 75 x 150 FOOT TUNNEL (18 fans, 50 foot tip diameter, H/D = .5) AT ONE-HALF SPEEDS AS INDICATED

Design Tip Speed ft/sec	350.00	410.00	628.00
RPM	66.66	78.26	120.00
Octave Band	Sound Power Levels re 10^{-13} watts		
3.9	140.1	142.9	150.4
7.8	142.5	145.5	153.2
15.6	143.7	147.1	155.5
31.2	143	146.8	156.5
62.5	140.8	144.9	155.5
125	138.1	142.2	153.2
250	135.1	139.3	150.4
500	132.1	136.3	147.4
1,000	129.1	133.3	144.4
2,000	126.1	130.3	141.4
4,000	123.1	127.3	138.4
8,000	120.1	124.3	135.4
16,000	117.1	121.3	132.4
OVERALL	149.8	153.4	162.8

TABLE 5.3

COMPARISONS OF FAN AND GAS TURBINE NOISE

POWER LEVELS re 10^{-13} WATTS

In Single Fan (350 ft/sec) at one-half speed

Frequency Band	31	63	125	250	500	1,000	2,000	4,000	8,000
L_w single fan (quietest) @ one-half speed	130.4	128.2	125.5	122.5	119.5	116.5	113.5	110.5	107.5
MS5000 Combined silenced intake and package L_w	117.5	115.5	112.5	107.5	102.5	96.5	101	110	112.5
MS5000 Exhaust L_w with large parallel baffle silencer	136	132	130.5	132	116.5	117.5	107.5	101.5	99
MS5000 Exhaust L_w with switchback silencer	115	105	99	94	86	81	72	67	80

SECTION 6

Cost Analysis, Large Scale V/STOL Wind Tunnel

6.0 The results of the cost analysis are tabulated in tables 6-1 through 6-6.

These prices are based on current market levels (September 1973) and do not include any contingency for possible estimating errors nor do they include an allowance for price escalation between September 1973 and the date of construction.

6.1 Electrical and Gas Turbine Drive System Costs

All of the subject equipment is manufactured by the General Electric Co. except the 110kV underground pipe cable.

Costs for most of the items which are manufactured by the General Electric Co. were obtained from published prices, adjusted for current market levels. Where published prices were not available, the prices were based on recent selling prices.

The 110kV underground cable cost was estimated from an April 1966 Federal Power Commission report on underground power transmission, escalated to reflect general price level increases since that date.

The installation cost estimate for the drive equipment is given as 30 percent of the cost of the equipment. This percentage number is based on experience gained from previous installations of similar equipment furnished for the NASA wind tunnels at the Ames, Lewis and Langley Research Centers.

6.2 Fan Costs

The fan costs are included in cost summary tables 6-1, 6-3 and 6-5.

Table 4-3, page 67A, tabulates fan costs based on the fans listed in table 2-1, reference #4. These costs were used to estimate the fan costs for the six 50 foot diameter fans used herein.

ALTERNATE	1A	1B	1C	2A	2B	2C
TOTAL SHAFT HORSEPOWER	435,000	435,000	435,000	435,000	435,000	435,000
TUNNEL CONFIGURATION	HYBRID CLOSED/OPEN	HYBRID CLOSED/OPEN	HYBRID CLOSED/OPEN	HYBRID CLOSED/OPEN	HYBRID CLOSED/OPEN	HYBRID CLOSED/OPEN
NUMBER OF FANS	18	18	18	18	18	18
FAN DATA:						
TYPE	ADJ. PITCH	ADJ. PITCH	ADJ. PITCH	ADJ. PITCH	ADJ. PITCH	ADJ. PITCH
TIP VELOCITY (FPS)	350	410	628	350	410	628
TIP DIAMETER (FEET)	50	50	50	50	50	50
RPM	133 1/3	156.52	240	133 1/3	156.52	240
SHAFT HORSEPOWER	24,000	24,000	24,000	24,000	24,000	24,000
COST ANALYSIS (# × 1000)						
A-C MOTORS	#11,183	#10,418	#8,714	#12,380	#11,649	#9,774
D-C MOTORS	#4,770	#4,248	#3,744	—	—	—
GEARS	—	—	—	—	—	—
Δ TRANSF., SWGR., CABLE, CONTROL	#8,871	#8,871	#8,871	#9,781	#9,781	#9,781
INSTALLATION OF ABOVE (@34%)	#7,530	#7,028	#6,275	6,648	#6,429	#5,867
SUB-TOTAL OF INSTALLED DRIVE COST	#32,354	#30,565	#27,604	#28,809	#27,859	#25,422
FAN	#13,010	#12,517	#10,327	#13,010	#12,517	#10,327
TOTAL (DRIVE + FAN)	#45,364	#43,082	#37,931	#41,819	#40,376	#35,749

Δ FROM TABLE #6-2

COST TABULATION
75'× 150' TUNNEL

TABLE #6-1

	18 ADJUSTABLE PITCH FANS HYBRID OPEN/CLOSED TUNNEL					
	85% A-C SYNCHRONOUS, 15% D-C MOTORS			100% A-C SYNCHRONOUS 15% CAPACITY RECTIFIER/INVERTER		
TIP SPEED (FT./SEC.)	350	410	628	350	410	628
ALTERNATE	1A	1B	1C	2A	2B	2C
HP/A-C MOTOR (CONTINUOUS)	16,320	16,320	16,320	19,200	19,200	19,200
HP/D-C MOTOR (CONTINUOUS)	2,880	2,880	2,880	—	—	—
3 - 115KV SW. BAYS	$81	$81	$81	$81	$81	$81
3 - 115KV O.C.B.	$160	$160	$160	$160	$160	$160
115KV CABLE	$1074	$1074	$1074	$1074	$1074	$1074
POWER TRANSFORMERS	(3-120) $973	(3-120) $973	(3-120) $973	(3-120) $954	(3-120) $954	(3-120) $954
METALCLAD SWGR.	$1,247	$1,247	$1,247	$1,447	$1,447	$1,447
POWER FACTOR CORRECTION	$488	$488	$488	$49	$49	$49
A-C/D-C POWER CONVERSION	$3,168	$3,168	$3,168	—	—	—
A-C/A-C POWER CONVERSION	—	—	—	$4,306	$4,306	$4,306
MOTOR FIELD EXCITATION	$270	$270	$270	$300	$300	$300
CONTROL AND REGULATING	$1,350	$1,350	$1,350	$1,350	$1,350	$1,350
3 - 1000KVA LCUS	$60	$60	$60	$60	$60	$60
SUB-TOTAL (TO TABLE 6-1)	$8,871	$8,871	$8,871	$9781	$9,781	$9,781

COST TABULATION
75'×150' TUNNEL

TABLE #6-2

ALTERNATE	3A	3B	3C	4A	4B	4C
TOTAL SHAFT HORSEPOWER	435,000*	435,000*	435,000*	435,000*	435,000*	435,000*
TUNNEL CONFIGURATION	HYBRID CLOSED/OPEN	HYBRID CLOSED/OPEN	HYBRID CLOSED/OPEN	HYBRID CLOSED/OPEN	HYBRID CLOSED/OPEN	HYBRID CLOSED/OPEN
NUMBER OF FANS	18	18	18	18	18	18
FAN DATA:						
TYPE	FIXED PITCH	FIXED PITCH	FIXED PITCH	FIXED PITCH	FIXED PITCH	FIXED PITCH
TIP VELOCITY (FPS)	350	410	628	350	410	628
TIP DIAMETER (FEET)	50	50	50	50	50	50
RPM	133 1/3	156.52	240	133 1/3	156.52	240
SHAFT HORSEPOWER	24,000*	24,000*	24,000*	24,000*	24,000*	24,000*
COST ANALYSIS (# × 1000)						
A-C MOTORS	#12,153	#11,435	#9,593	#12,936	#11,871	#10,536
D-C MOTORS	—	—	—	—	—	—
GEARS	—	—	—	—	—	—
Δ TRANSF., SWGR., CABLE, CONTROL	#19,332	#19,332	#19,332	#26,440	#26,440	#26,440
INSTALLATION OF ABOVE (30%)	#9,446	#9,230	#8,678	#11,813	#11,493	#11,093
SUB-TOTAL OF INSTALLED DRIVE COST	#40,931	#39,997	#37,603	#51,189	#49,804	#48,069
FAN	#10,407	#9,716	#8,479	#10,407	#9,716	#8,479
TOTAL (DRIVE + FAN)	#51,338	#49,713	#46,082	#61,596	#59,520	#56,548

Δ FROM TABLE #6-4
* HAS 1.125/1 SPEED RANGE AT
CONSTANT HORSEPOWER

COST TABULATION
75'×150' TUNNEL

TABLE # 6-3

TIP SPEED (FT./SEC.)	350	410	628	350	410	628
	18 FIXED PITCH FANS HYBRID OPEN/CLOSED TUNNEL					
	100% SYNCHRONOUS MOTORS 2-170MW RECTIFIER/INVERTERS			100% SYNCHRONOUS MOTORS 18-THYRISTOR CYCLOCONVERTERS		
ALTERNATE HP/A-C MOTOR (CONTINUOUS)	3A 19,200 *	3B 19,200 *	3C 19,200 *	4A 19,200 *	4B 19,200 *	4C 19,200 *
115 KV SW. BAYS	(2) $54	(2) $54	(2) $54	(3) $81	(3) $81	(3) $81
115 KV AIR CIRCUIT BREAKER	(2) $154	(2) $154	(2) $154	(3) $231	(3) $231	(3) $231
POWER TRANSFORMERS	(2) $1,749	(2) $1,749	(2) $1,749	(3) 942	(3) $942	(3) $942
METALCLAD SWITCHGEAR	$1,262	$1,262	$1,262	$96	$96	$96
STATION CLASS SWITCHGEAR	$111	$111	$111	$1,105	$1,105	$1,105
POWER FACTOR CORRECTION	$1,760	$1,760	$1,760	$4,950	$4,950	$4,950
AUXILIARY TRANSFORMERS	$79	$79	$79	$45	$45	$45
A-C/D-C POWER CONVERSION	$11,250	$11,250	$11,250	—	—	—
A-C/A-C POWER CONVERSION	$1,143	$1,143	$1,143	$17,280	$17,280	$17,280
MOTOR FIELD EXCITATION	$360	$360	$360	$300	$300	$300
CONTROL AND REGULATING	$1,350	$1,350	$1,350	$1,350	$1,350	$1,350
3-1000 KVA LCUS	$60	$60	$60	$60	$60	$60
SUB-TOTAL (TO TABLE 6-3)	$19,332	$19,332	$19,332	26,440	$26,440	$26,440

* HAS 1.125/1 SPEED RANGE AT CONSTANT HORSEPOWER

COST TABULATION
75'×150' TUNNEL

TABLE #6-4

ALTERNATE	5A	5B	5C	6A	6B	6C
TOTAL SHAFT HORSEPOWER	435,000*	435,000*	435,000*	435,000*	435,000*	435,000*
TUNNEL CONFIGURATION	HYBRID CLOSED/OPEN	HYBRID CLOSED/OPEN	HYBRID CLOSED/OPEN	HYBRID CLOSED/OPEN	HYBRID CLOSED/OPEN	HYBRID CLOSED/OPEN
NUMBER OF FANS	18	18	18	18	18	18
FAN DATA:						
TYPE	FIXED PITCH	FIXED PITCH	FIXED PITCH	FIXED PITCH	FIXED PITCH	FIXED PITCH
TIP VELOCITY (FPS)	350	410	628	350	410	628
TIP DIAMETER (FEET)	50	50	50	50	50	50
RPM	$133\frac{1}{3}$	156.52	240	$133\frac{1}{3}$	156.52	240
SHAFT HORSEPOWER	24,000*	24,000*	24,000*	24,000*	24,000*	24,000*
COST ANALYSIS (\$ ×1000)						
A-C MOTORS	\$10,218	\$10,218	\$17,415	—	—	—
GAS TURBINES	—	—	—	\$31,722	\$31,722	\$31,722
D-C MOTORS	—	—	—	\$4,698	\$4,284	\$3,096
GEARS	\$13,590	\$11,979	—	\$8,586	\$6,869	\$4,770
△TRANSF., SWGR., CABLE, CONTROL	\$17,676	\$17,676	\$18,336	\$4,685	\$4,685	\$4,685
INSTALLATION OF ABOVE (EST. @ 30%)	\$12,445	\$11,962	\$10,725	\$14,907	\$14,268	\$13,282
SUB-TOTAL OF INSTALLED DRIVE COST	\$53,929	\$51,835	\$46,476	\$64,598	\$61,828	\$57,555
FAN	\$10,407	\$9,716	\$8,479	\$10,407	\$9,716	\$8,479
TOTAL (DRIVE + FAN)	\$64,336	\$61,551	\$54,955	\$75,005	\$71,544	\$66,034

COST TABULATION
75'×150' TUNNEL

TABLE #6-5

△ FROM TABLE #6-6
* HAS 1.125/1 SPEED RANGE AT CONSTANT HORSEPOWER

	18 FIXED PITCH FANS HYBRID OPEN/CLOSED TUNNEL					
	100% A-C DOUBLY-FED WOUND ROTOR INDUCTION MOTORS			TWO-SHAFT GAS TURBINE AND 10% D-C MOTOR		
TIP SPEED (FT./SEC.)	350	410	628	350	410	628
ALTERNATE	5A	5B	5C	6A	6B	6C
HP/GAS TURBINE @ 95°F INLET	—	—	—	24,000*	24,000*	24,000*
HP/A-C MOTOR	24,000*	24,000*	24,000*	—	—	—
HP/D-C MOTOR	—	—	—	2,500*	2,500*	2,500*
115 KV SWITCH BAYS	(4) $108	(4) $108	(4) $108	(1) $27	(1) $27	(1) $27
115 KV BREAKERS	308	308	308	53	53	53
115 KV CABLE	1,432	1,432	1432	358	358	358
POWER TRANSFORMERS	1,302	1,302	1,302	148	148	148
STATION CLASS SWITCHGEAR	512	512	512	—	—	—
METALCLAD SWITCHGEAR	1,098	1,098	1,098	93	93	93
POWER FACTOR CORRECTION	2,376	2,376	3,036	270	270	270
A-C/D-C POWER CONVERSION	—	—	—	2,358	2,358	2,358
A-C/A-C POWER CONVERSION	9,135	9,135	9,135	—	—	—
CONTROL AND REGULATING	1,350	1,350	1,350	1,350	1,350	1,350
LOAD CENTER UNIT SUBSTATIONS	55	55	55	28	28	28
SUB-TOTAL (TO TABLE 6-5)	17,676	17,676	18,336	4,685	4,685	$4,685

* HAS 1.125/1 SPEED RANGE AT CONSTANT HORSEPOWER

COST TABULATION
75 × 150 TUNNEL

TABLE 6-6

SECTION 7

Ames 40'x80' Wind Tunnel

Additional Electric Drive

Alternates C and D

7.0 Introduction

As a sub-contractor to John A. Blume and Associates the General Electric Co. performed a study of a wind tunnel power system employing adjustable pitch fans and a drive motor system capable of operating as follows:

Mode #1

- Fans set at full pitch
- Motors to operate from 5% to 50% of top rated speed as adjustable speed, adjustable frequency synchronous motors. (This required only 15% of top rated fan horsepower)
- The adjustable frequency will be obtained from thyristor rectifier-inverter power conversion equipment.

Mode #2

- Synchronous motors run at constant speed and connected to the 60Hz power system.
- Wind tunnel air speed is adjusted from 50% to 100% of rated air speed via pitch control of the fans.

When mode #2 operation is desired, the drives will be accelerated to top rated motor speed with the fans depitched, using the 15% capacity adjustable frequency thyristor power conversion equipment. The synchronous motors will then be synchronized to the 60Hz power system after which Mode #2 operation can commence.

This supplement to the 40'x80' wind tunnel study considers two alternative drive systems, both employing fixed pitch fans and adjustable speed drives.

7.1 Fixed Pitch Fans and Adjustable Speed Drives Versus Adjustable Pitch Fans and Constant Speed Drives

The mechanical simplicity of a gearless electric motor driving a fixed pitch fan cannot be matched by any other fan-drive system. A few of its superior characteristics are tabulated below:

A. High Reliability

1. Simplicity of fixed pitch fan blade attachment permits designs, having lowest stresses at blade attachment point. This minimizes probability of mechanical failure at attachment point caused by steady-state or cyclic fatigue stresses.
2. Absence of moving parts within the hub eliminates possibility of wear and subsequent blade vibration and backlash.
3. Absence of moving parts within the hub eliminates need for lubrication of hub components.

B. Superior Air Flow Profile

The fixed pitch fan operating at adjustable speed inherently results in a more uniform air velocity profile from hub to tip of the fan than does an adjustable pitch, constant speed fan. The warp of the blade remains constant in an adjustable pitch fan as it changes its pitch. Hence reductions in air flow of adjustable pitch fans create a circulatory component of flow from hub to tip of the fan.

In a sub-sonic tunnel, this nonuniform air velocity from hub to tip of the fans can result in a undesirable air velocity variations at the wind tunnel test section.

C. Minimum Noise Power Level

The noise power produced by a fan is a function of its tip velocity. At 50% flow, the fixed pitch, adjustable speed fan experiences a 15db reduction of noise. The constant speed, adjustable pitch fan can be expected to create a constant maximum noise for all tunnel air flow conditions above 50% of rated tunnel air speed.

D. Highest Resolution of Air Flow Adjustment and Lowest Air Flow Drift with Time

The proposed adjustable speed electric drive systems will have modern solid-state digital speed regulators. The resolution of the speed setting function and the inherently low time drift of the precision crystal controlled reference frequencies make the adjustable speed fixed pitch fan systems superior to the adjustable pitch fan method of air flow adjustment. The latter has friction and backlash not present in the adjustable speed control systems and requires rotating mechanical and/or hydraulic and/or electrical connections to the rotating hub assembly.

7.2 Synchronous Motors

The proposed synchronous motors will be directly coupled to their associated fixed pitch fan.

Because this is to be a repowering of an existing wind tunnel,it is desirable to minimize the weight of the synchronous motors so that the existing motor foundations can be reused.

Preliminary motor design investigations indicated that:

3.1 The synchronous motor outside diameter cannot be less than the seventeen feet (17') diameter employed in Alternates A and B of the J.A. Blume study.

3.2 The adjustable speed alternates C and D (to be described later in this supplement) can also be built in the seventeen foot O.D. frame and will be essentially the same size as the motors for Alternates A and B.

It would be desirable from an aerodynamic standpoint to reduce the motor nacelle diameter from the 20 feet design proposed via the J.A. Blume report to something smaller because the smaller nacelle diameter would allow slightly higher test section air velocities. However, it does not appear that this can be done by reducing motor diameter. If nacelle diameter is reduced, it must be done by integrating the design of motor frame into the outer shell of the nacelle. This would seriously affect the maintainability of the motor because its stator could no longer be shifted axially on a base as is necessary to rewind a motor of this size in installations where disassembly by cranes is not feasible.

It does not appear at this time that reducing the nacelle diameters below the 20 foot diameter proposed by Blume would result in sufficient gain in test section velocity to offset the resulting marginal maintainability of the motors or the complications of supporting a round frame motor without feet.

7.3 Alternate C, Fixed Pitch Fans with Adjustable Speed Drives Consisting of Synchronous Motors and One Large Thyristor Rectifier - Inverter Frequency Changer.

Figure #7.1 is the electrical power one-line diagram for this alternate.

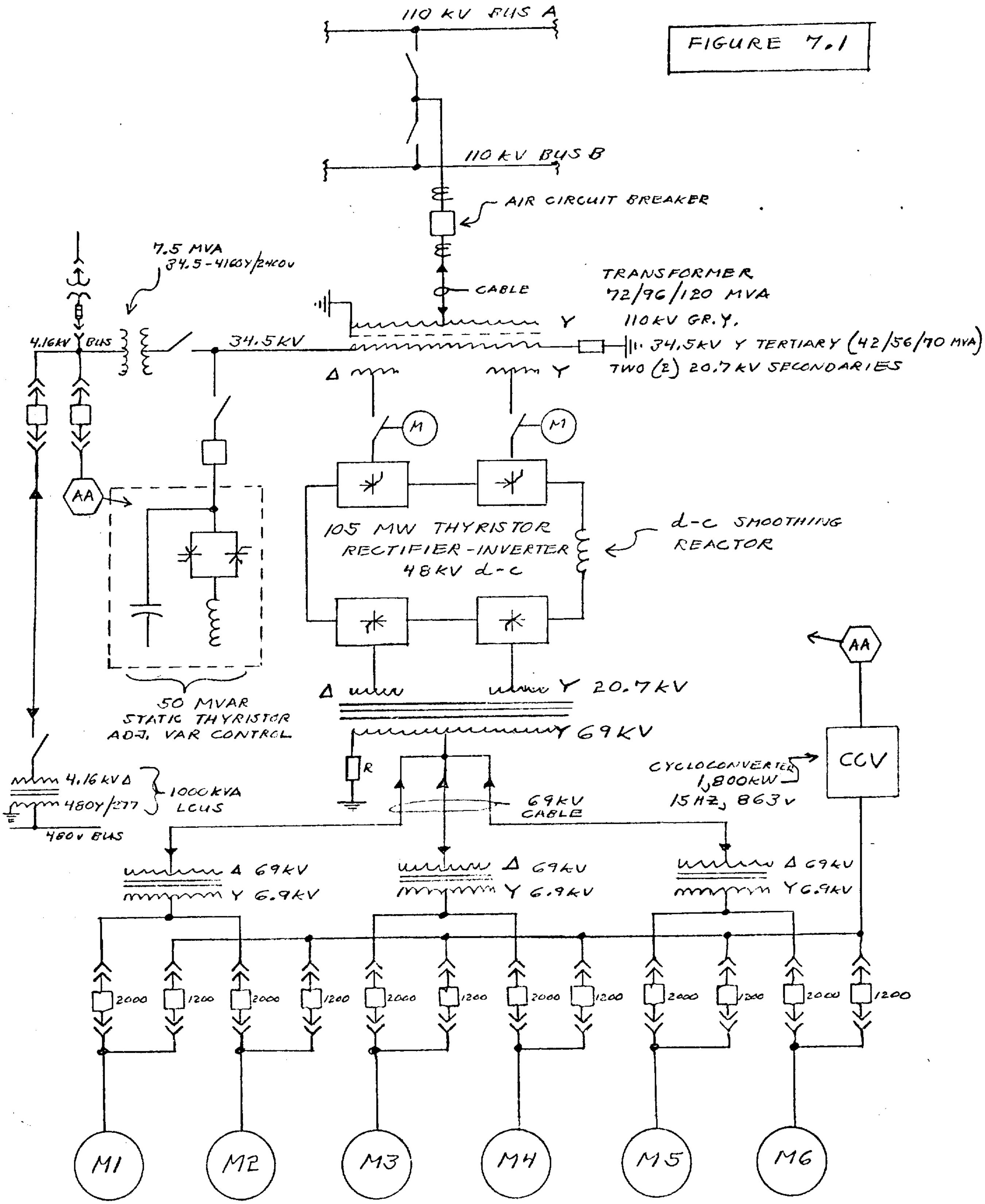
The synchrnous motors are operated at adjustable speed via an adjustable frequency power conversion system.

For motor speeds from 5% to 25% of rated fan speed, the adjustable frequency is obtained from an 1,800 kW thyristor cycloconverter.

For motor speeds from 25% to 100% of rated fan speed, the adjustable frequency is obtained from a 105.6 MW thyristor rectifier-inverter.

A 50 MVAR static thyristor adjustable var control, operating from a 34.5 kV tertiary on the main constant frequency transformer, supplies continuously adjustable control of magnetizing kilovars. This unit will be switched on and off the 34.5 kV bus when the main thyristor rectifier is not in service. Hence

FIGURE 7.1



(6) 18,000 HP
SYNCHRONOUS MOTORS
HAVING 2-HR. 25% O.L.
OF 22,500 HP AT 0.85 P.F.

SKETCH MDH-92493-1

M.D.H.

40×80 WIND TUNNEL
ALTERNATE C, 6 FIXED PITCH FANS
POWER ONE-LINE DIAGRAM
FOR
NASA AMES RESEARCH CENTER
SYNCHRONOUS MOTORS WITH RECTIFIER/INVERTER

miscommutation of the main rectifier-inverter, due to capacitor switching transients, will be avoided.

The var control is smoothly and continuously adjustable via the phase control of the back-to-back thyristors in series with the inductive reactance. The shunt capacitors will be tuned to act as harmonic filters for the harmonics produced by the var control and by the main thyristor rectifier.

The inverter is not used until the drive is operating at or above 25% of rated speed. Hence the inverter can be a simple line-commutated inverter which derives its commutating kVAR from the 0.85 P.F. synchronous motors which it serves.

A 69kV table connection is shown between the rectifier-inverter and the motor transformers. This makes it practical to to install the two main transformers, the main rectifier inverter and the Hz static var control at a physical location remote from the wind tunnel. The three 69kV to 6.9kV transformers, the 6.9kV switchgear and the 1800 kW cycloconverter would be installed as close to the drive motors as is physically possible in order to minimize the length of the high current 6.9kV motor circuits.

The 69 kV intermediate voltage was chosen because cable and transformers are economical at this voltage level.

The 69kV could also be readily switched to other future facilities which required adjustable frequency power.

The synchronous motor voltage was selected to be 6,600 volts. 6,600 volt motors at 0.85 PF can be made to fit into the desired 17' O.D. frame size where 13.8kV 0.85 PF motors result in a marginal design in a 17' O.D. frame. The higher voltage would result in lower cable and circuit breaker costs, however, the lower cost of the 6900 volt motors tend to offset these higher costs.

The synchronous motors are rated as follows:

18,000 HP Continuously
22,500 HP for two hours
180 RPM
6,600 Volts
3 Phase
60 Hertz
0.85 Power Factor
40 Poles
- Class F Insulation
- Separately forced ventilated for reduced speed operation to 5% of rated speed when connected to a fan load.

The recitifer/inverter is rated at 105.6 MW for two hours and employs high voltage thyristor sub-assemblies similar in design to those which have been in service at the Eel River Station of the New Brunswick Electric Power Commission (Canada)

The Eel River Station has 160/176 MW rectifier inverters, continuous /8 hours. Only 60% of the cells required in the Eel River converter will be required here to attain the 105.6MW rating.

7.4 Alternate D, Fixed Pitch Fans with Adjustable Speed Drives Consisting of Synchronous Motors and Individual Thyristor Cycloconverters.

Figure 3.2.4 describes the one-line diagram for this system.

The individual cycloconverters allow frequency adjustment from zero to approx. 36 Hertz.

The synchronous motors would be designed for 36 Hertz, unity power factor and hence will have fewer electrical poles (24 Poles) than the 60 Hertz (40 Pole) motor of Alternate C.

The 24 Pole unity power factor motor will have essentially the same weights and dimensions as the 40 pole, 0.85 P.F. motor of Alternate C.

Because large, high voltage cycloconverters have not been developed at this time, individual low voltage (1700 volt) cycloconverters have been proposed for this alternate.

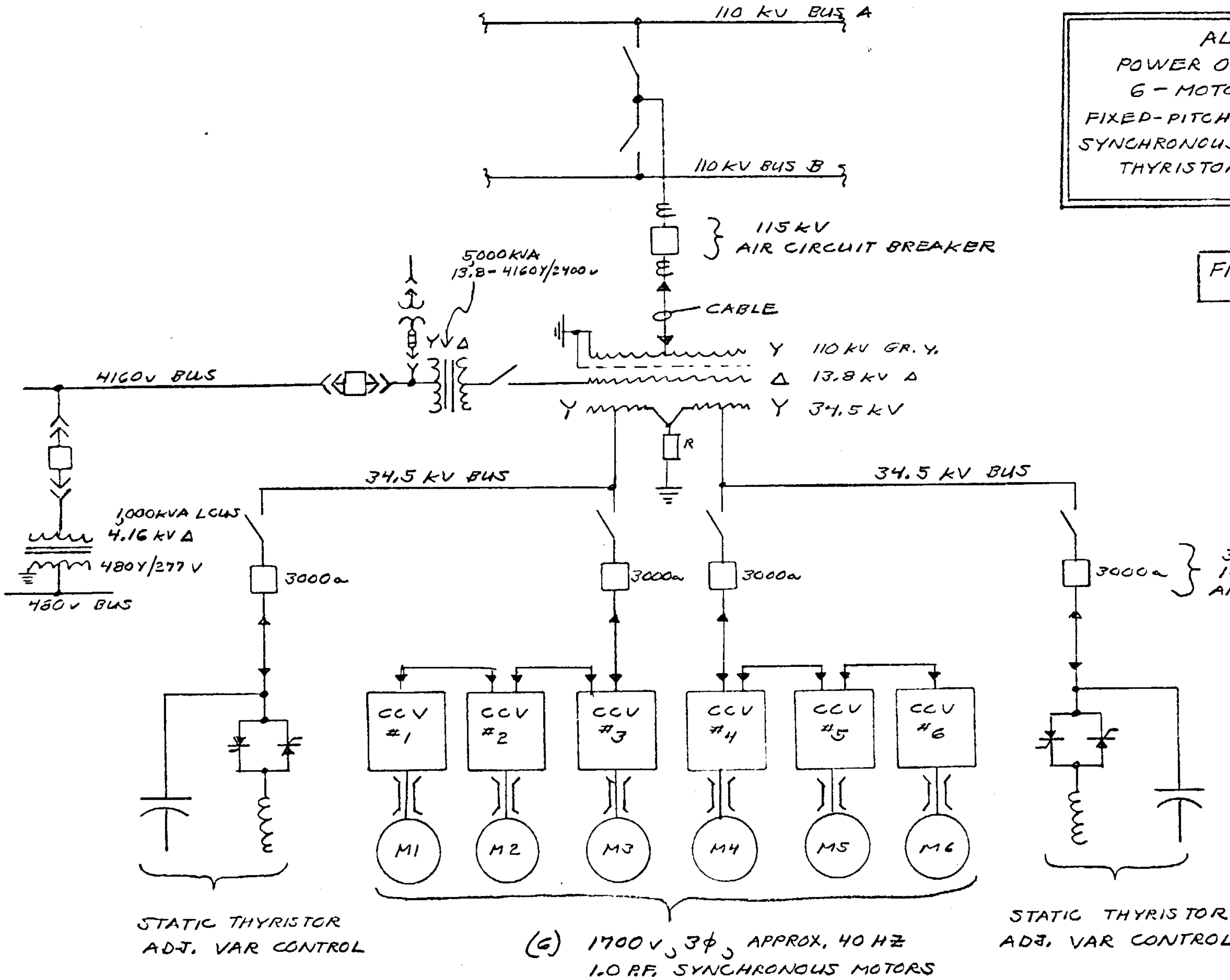
The synchronous motors will be rated as follows:

18,000 Hp Continuously
22,500 HP for two hours
180 RPM
1,700 Volts
3 Phase
36 Hertz
1.0 Power Factor
24 Poles

- Class F Insulation
- Separately forced ventilated for reduced speed operation to 5% of rated speed when connected to a fan load.

ALTERNATE #4
POWER ONE-LINE DIAGRAM
6-MOTOR MODULE
FIXED-PITCH FANS, ADJUSTABLE SPEED
SYNCHRONOUS MOTORS WITH
THYRISTOR CYCLOCONVERTERS

FIGURE 3.2.4



SKETCH MDH-92473-2
M.D. Horton

The cycloconverters are rated as follows:

Input

34.5 kV

3 Phase

60 Hertz

Output

14,000/17,500 kVA

Continuous/two-hours

1,700 Volts line-to-linee

3 Phase

36 Hertz

12 Pulses per input
a-c cycle

A 34.5 kV intermediate voltage was selected because of reduced switchgear and cable cost and because the static thyristor Var control has minimum cost at this voltage.

The two static var controls, required for system power factor correction, will each be rated for 70 MVAR.

TABLE 7-2

SUMMARY OF 40'x80' WIND TUNNEL DRIVE AND FAN COSTS

ALTERNATE	C	D
Motor 60Hz RPM	180	180
HP/a-c Motor (Cont.)	18,000	18,000
HP/a-c Motor (2-Hours)	22,500	22,500
COSTS		
6- Motors	$3,216,720	$3,327,756
1- 105.6 MW thyristor rectifier inverter	$3,795,000	
6- 17,500 KVA cycloconverters		$5,400,000
1- 1,700 KW cycloconverters & speed regulators	$ 528,000	
1- Main transformer	$ 341,203	$ 314,557
1- Inverter transformer	$ 251,626	
3- Local motor transformer	$ 335,461	
1- 4160V aux transformer	$ 30,992	$ 22,634
2- 115KV potential transformers	$ 6,000	$ 6,000
1- Lot of switchgear, protective relaying and metering	$ 429,424	$ 403,547
1- Static var control	$ 600,000	$1,540,000
1- Master control and regulating panel	$ 360,000	$ 360,000
2- Unit substations	$ 126,492	$ 126,492
6- Fan shaft and bearing	$ 662,400	$ 662,400
1- Credit for main transformer and relaying not included in table 6-1 of GE report to J.A. Blume	$ -289,000	$ -289,000
Sub-total drive costs	$10,394,318	$11,874,386
6- Fans, spinners and stator blading (24 month program)	$ 3,108,609	$ 3,108,609

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